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AFIT/GAE/AA/81D-31

AN EXPERIMENTAL STUDY OF RECTANGULAR AND CIRCULAR THRUST AUGMENTING EJECTORS

THESIS

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CAPT USAF

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THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by

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Capt USAF

Graduate Aerospace Engineering

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Preface

The purpose of this investigation was to determine the effect of primary nozzle configuration and diffuser geometry on the thrust augmentation performance of both rectangular and circular ejectors. This investigation was essentially a continuation of work conducted in 1979 by Maj Kedem, Israeli Air Force and work done in 1980 by Capt Reznick, USAF. Both conducted their research while students at the Air Force Institute of Technology.

The same basic equipment and test instrumentation designed and used by Kedem and Reznick were used in this investigation. Some minor modifications were accomplished to increase the range of parameters tested.

I wish to take this opportunity to express my appreciation to the entire staff of the AFIT fabrication shop for their excellent support in fabricating the components required to modify the original ejectors. I also wish to thank: Dr. Franke, my faculty advisor, for his guidance and encouragement; Dr. Nagaraja, my thesis sponsor, for his research assistance; and Capt Reznick, my project predecessor, for his assistance in familarizing me with the test equipemnt and for his valuable suggestions concerning hardware modifications and areas of research. The final and most important thank you goes to my wife Jackie and daughter Elizabeth for their personal support during the last 18 months.

Gregory Unnever

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List of Symbols

A	Area (in^2)
A_0	Cross Section Area of Primary Nozzle Exit(s) (in^2)
A_2	Cross Section Area of Mixing Chamber (in^2)
A_3	Cross Section Area of Diffuser Exit (in^2)
A_2/A_0	Inlet Area Ratio
A_3/A_2	Exit Area Ratio
F_i	Isentropic Thrust (lbf)
F_m	Measured Thrust (lbf)
h	Distance Between Primary Nozzles (Measured Along Perimeter)
P_a	Ambient Pressure (in Hg)
P_s	Static Pressure (in Hg)
P_t	Total Pressure (in Hg)
R	Gas Constant (lbf ft/slug R)
T	Temperature (r)
V	Velocity (fps)
α	Primary Fluid Injection Angle (deg)
ρ	Density ($slug/ft^3$)
$\emptyset$	Isentropic Thrust Augmentation
ψ	Diffuser Wall Angle (deg)

Abstract

A short rectangular ejector and two circular ejectors were tested to determine the effects of primary nozzle configuration and geometry on thrust augmentation. The primary nozzle configurations consisted primarily of slot nozzles which injected fluid parallel to the diffuser walls and achieved Coanda type flow at the throat.

Results of the rectangular ejector tests indicate that thin plates installed in the mixing chamber or the diffuser, increase mixing but decrease thrust augmentation. A continuous slot nozzle, modified to create four discrete jets at the inlet, improved mixing and thrust augmentation as compared to the original design. Thrust augmentation ratio increased from 1.4 to 1.58.

The circular ejector primary nozzles consisted of a continuous slot "torus" nozzle and individual slot nozzles which could be symmetrically placed around the inlet periphery. A nozzle configuration using 16 slot nozzles on the periphery of the inlet face gave the best performance. A thrust augmentation ratio of 2.0 was achieved with this configuration.

AN EXPERIMENTAL STUDY OF RECTANGULAR AND CIRCULAR THRUST AUGMENTING EJECTORS

I Introduction

Background

A thrust augmenting ejector is a device used for increasing or "augmenting" the thrust of a primary propulsive nozzle. With an ejector, thrust is increased by the transfer of kinetic energy from the primary fluid jet to a larger mass of secondary fluid. This secondary fluid is drawn or "entrained" into the inlet duct primarily as a result of viscous shear. Energy transfer is then accomplished through turbulent mixing of the two fluids in a mixing chamber. The resulting mixed flow is normally decelerated by a diffuser to ambient conditions. Net change in momentum of the fluids is increased and the resulting thrust is larger than the thrust that would have occurred if the primary nozzle acted alone. Details of this process have been discussed by von Kármán (Ref 1) and more recently by Porter and Squyers (Ref 2). A schematic of an ejector can be seen in Fig 1.

A review of current literature indicates that three major design concepts are currently used in the design and testing of thrust augmenting ejectors. They are:

1. Entrainment of secondary fluid using Coanda flow at the throat.

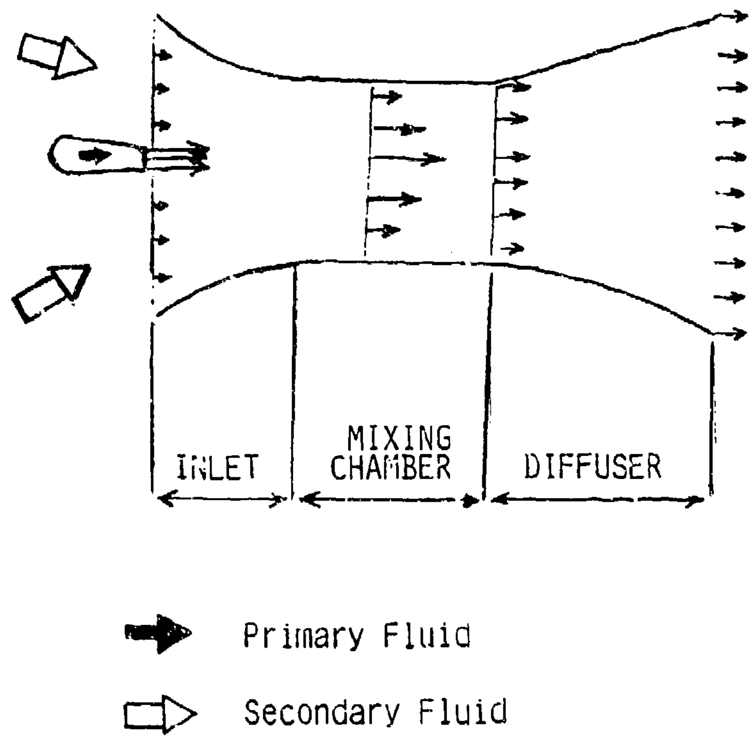


Figure 1. Thrust Augmenting Ejector Schematic

2. Increased mixing of primary and secondary flow by using multiple "hypermixing" nozzles.

3. Injection of primary fluid near the ejector duct walls (i.e. energizing the boundary layer and optimizing diffuser performance).

Campbell and von Ohain (Ref 3) designed and tested an ejector based on the above. Quoted thrust augmentation ratios were in excess of 2.5. A more recent ejector, designed and tested by Alperin and Wu (Ref 4) incorporates a curved inlet, nozzles located along the inlet periphery and diffuser blowing. Published thrust augmentation ratios were 1.9 to 2.0. Finally, recent work at the Air Force Institute of Technology, has confirmed the superior performance of Coanda type flow at the inlet. Reznick (Ref 5) tested an axisymmetric circular ejector with eight discrete nozzles positioned around the inlet. This configuration achieved a thrust augmentation of nearly 2.0.

Purpose and Objectives

The objectives of this study are:

1. Install thin aluminum plates in the mixing chamber and diffuser sections of a rectangular ejector with known performance and determine the effect on mixing and thrust augmentation.

2. Modify the existing continuous slot nozzles of the above ejector so as to create discrete jets at the inlet and determine the influence of these modified nozzles on mixing and thrust augmentation.

3. Investigate the fluid injection and geometry parameters that affect the thrust augmentation of axisymmetric, circular ejectors. The specific parameters to be investigated are:

a) The ratio of the mixing chamber area to the primary nozzle(s) exit area (A_2/A_0)

b) The ratio of the diffuser exit area to the mixing chamber area (A_3/A_2)

c) The ratio of the diffuser exit area to the primary nozzle(s) exit area (A_3/A_0), i.e. a combination of items a and b

d) Fluid injection angle (α)

e) The influence of size, position and number of primary nozzles on thrust augmentation.

Scope of Experimental Work

The ejectors were tested on a static test stand under steady state conditions. Primary nozzle pressure readings and ejector thrust measurements were taken during each test run to determine the isentropic thrust augmentation ratio, $\emptyset$. This index of thrust augmentation is a widely used and generally accepted definition.

In addition to thrust augmentation, diffuser exit velocity profiles were determined for certain configurations. The average diffuser exit velocity was less than 100 fps with most velocities less than 70 fps. The ambient temperature in the test room ranged from 60F to 80F. Temperature was not a factor in thrust augmentation calculations and its influence on the velocity calculations was minimal. The ratio of primary to ambient pressure ranged from 1 to 1.14 for this low pressure investigation. The primary nozzle exit velocity was in the range of 300 fps to 490 fps for most of the testing.

II Experimental Apparatus and Procedures

Introduction

The experimental equipment consisted of a rectangular ejector, two axisymmetric circular ejectors, a circular wood frame (used for free thrust measurements), four types of primary nozzles, laboratory air, a strain gage load cell, and necessary instrumentation.

Rectangular Ejector

The Kedem designed ejector (Ref 6) as modified by Reznick was tested with and without aluminum plates installed in the mixing chamber and diffuser section. The plates spanned the entire width of the ejector (6.5 in), were 0.125 in thick and varied in length from one to three inches. Edges were either rounded or knife edge. Plate position was identified relative to the inlet plane, the duct wall and angle of attack from the ejector centerline. Figures A-1 thru A-3, Appendix A provide ejector configuration details.

The dual primary nozzles were tested in their original configuration and later modified to create eight discrete jets at the inlet. Aluminum inserts, 0.625 in thick, were placed along the span of the nozzle exit. These inserts reached completely back into the plenum chamber of the nozzle and therefore created discrete jets at the nozzle exit. The rectangular ejector can be seen in Fig 2, an original and a modified nozzle can be seen in Fig 3.

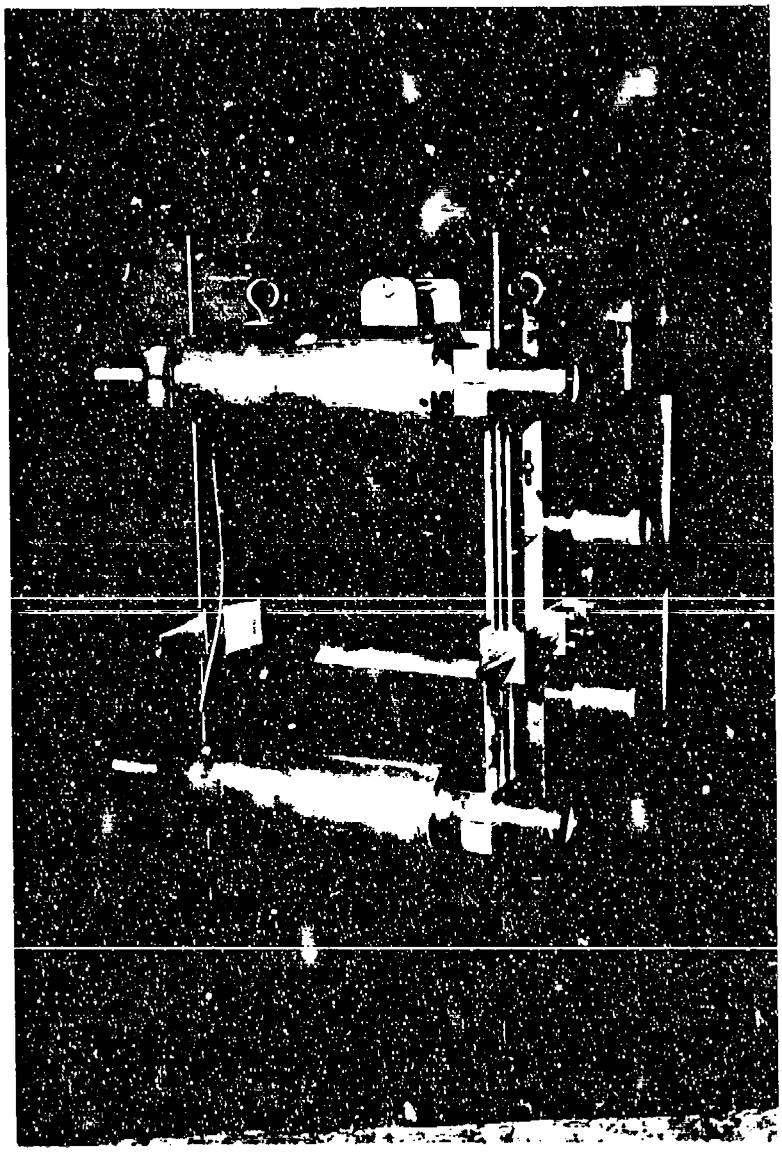


Figure 2. Photograph of Rectangular Ejector

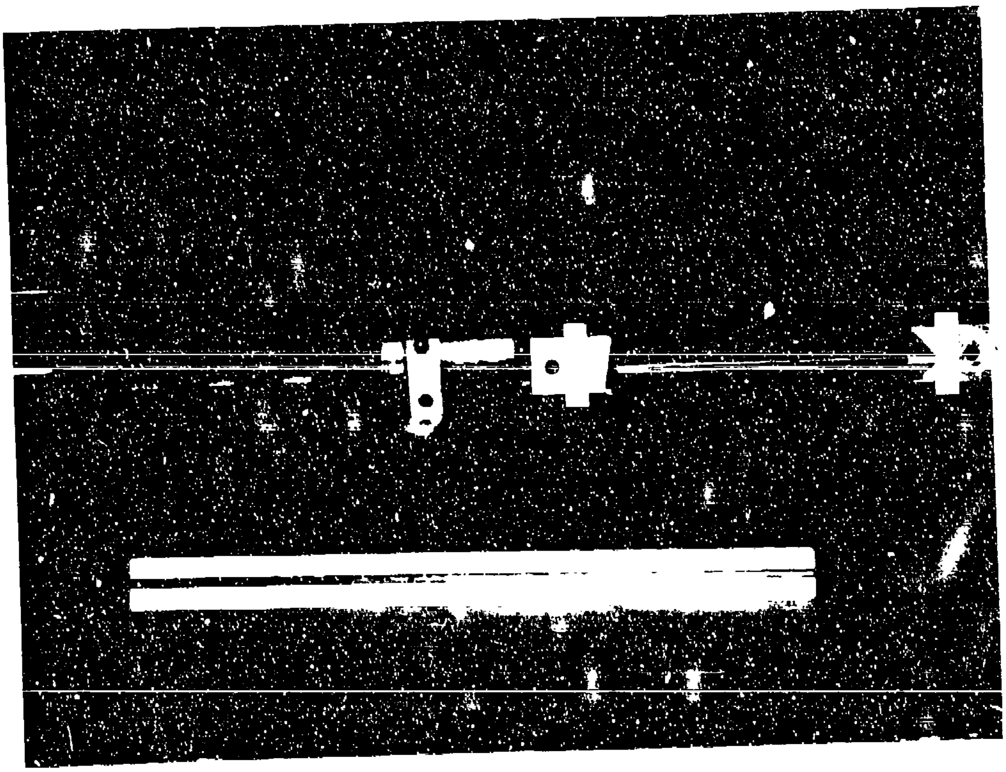


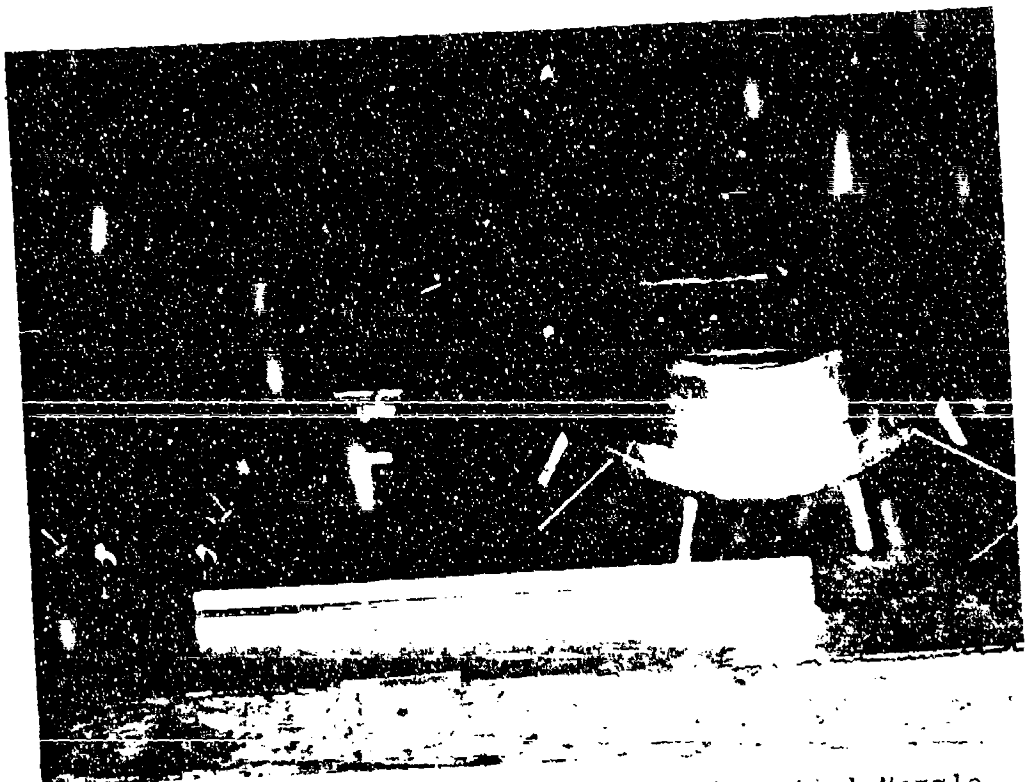
Figure 3. Photograph of Original and Modified Primary Nozzles Used in Rectangular Ejector

Circular Ejectors

The two circular ejectors used in this investigation were originally designed and tested by Reznick. The smaller ejector had a mixing chamber diameter of 4.4 inches and the larger ejector had a 6 inch mixing chamber diameter. Both ejectors had inlets possessing a 2 inch radius of curvature, which allowed the various primary nozzles to be mounted and tested on either ejector. Both ejectors had detachable, conic diffuser sections. Details of the diffuser configurations tested can be found in Appendix A, Tables A-2 and A-3.

Four types of primary fluid injection nozzles were tested. These included the original eight circumferential nozzles (slot length 0.96 in, gap 0.065 in), eight adjustable circumferential nozzles (slot length 0.96 in, gap 0.065 in), eight spoke nozzles (slot length 0.95 in, gap 0.045 in) and finally an annular "torus" nozzle (outside diameter was 6 in, slot gap 0.065 in). These nozzles are shown in Fig 4.

The eight adjustable nozzles were essentially the same nozzles as the original eight; however, their relative positions along the inlet could be adjusted to five locations (Fig 5). Fluid injection angle could be varied by pivoting the nozzles. The spoke nozzles were fabricated by modifying earlier slot nozzles which had spanned the entire inlet. Their lengths were reduced to limit drag effects and allow the center section of the inlet plane to be free of flow blockage. These spoke nozzles were combined with eight



Note: (left to right) Original Circumferential Nozzle, Adjustable Circumferential Nozzle, Spoke Nozzle, Torus Nozzle

Figure 4. Photograph of the Different Primary Nozzles Used in Circular Ejectors

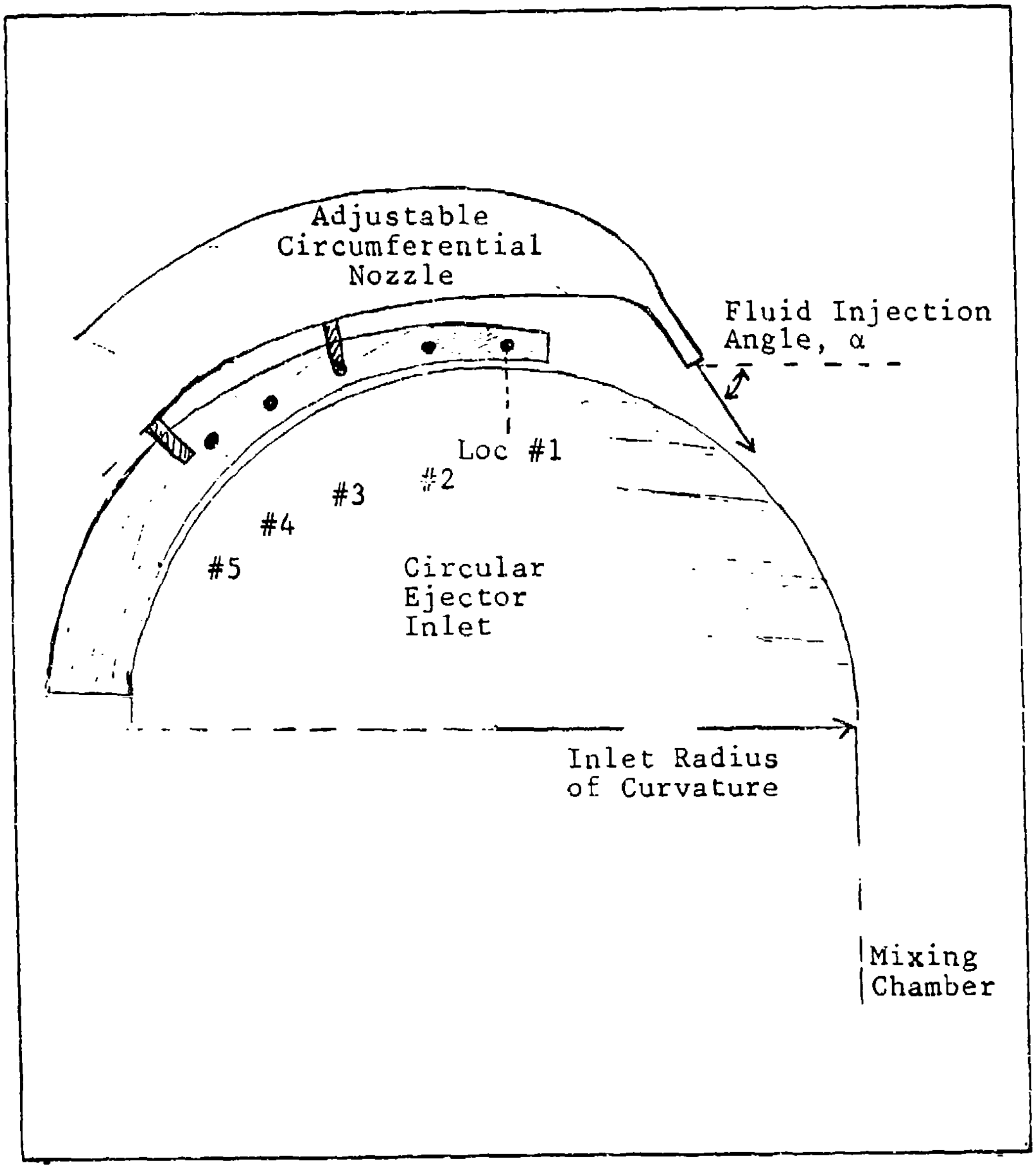


Figure 5. Adjustable Circumferential Nozzle

circumferential nozzles, creating an alternating slot configuration. This configuration was similar to the alternating slot nozzles tested by Mefferd and Bevilaqua (Ref 7). The primary nozzle configurations tested during this investigation are shown in Fig 6. Figure 7 is a photograph of the large ejector with twelve circumferential nozzles installed.

Test Stand

The test stand was the same as used in an earlier study (Ref 5). It consisted of a pendulum, manufactured from 3 in pipe, which pivoted about two annular bearings mounted in a plumbing "Tee". Laboratory air was supplied to the primary nozzles from taps in the pendulum via tygon tubing (Fig 8).

Strain Gage

Thrust was measured by a system of cables and adjustable pulleys that connected the ejector to a strain gage load cell. Another set of cables also connected the ejector to a simple weight platform used for calibrating the strain gage. Method of calibration and estimated accuracy of results can be found in Appendix C.

Thrust Calibration Ring

A wood ring with a 6 in ID and an 8 in OD was manufactured to measure the primary nozzle(s) free thrust. The ring was installed on the test stand and provided a mount for the different nozzles (Fig 9). Thrust measurements were taken using the same procedures as during ejector tests.

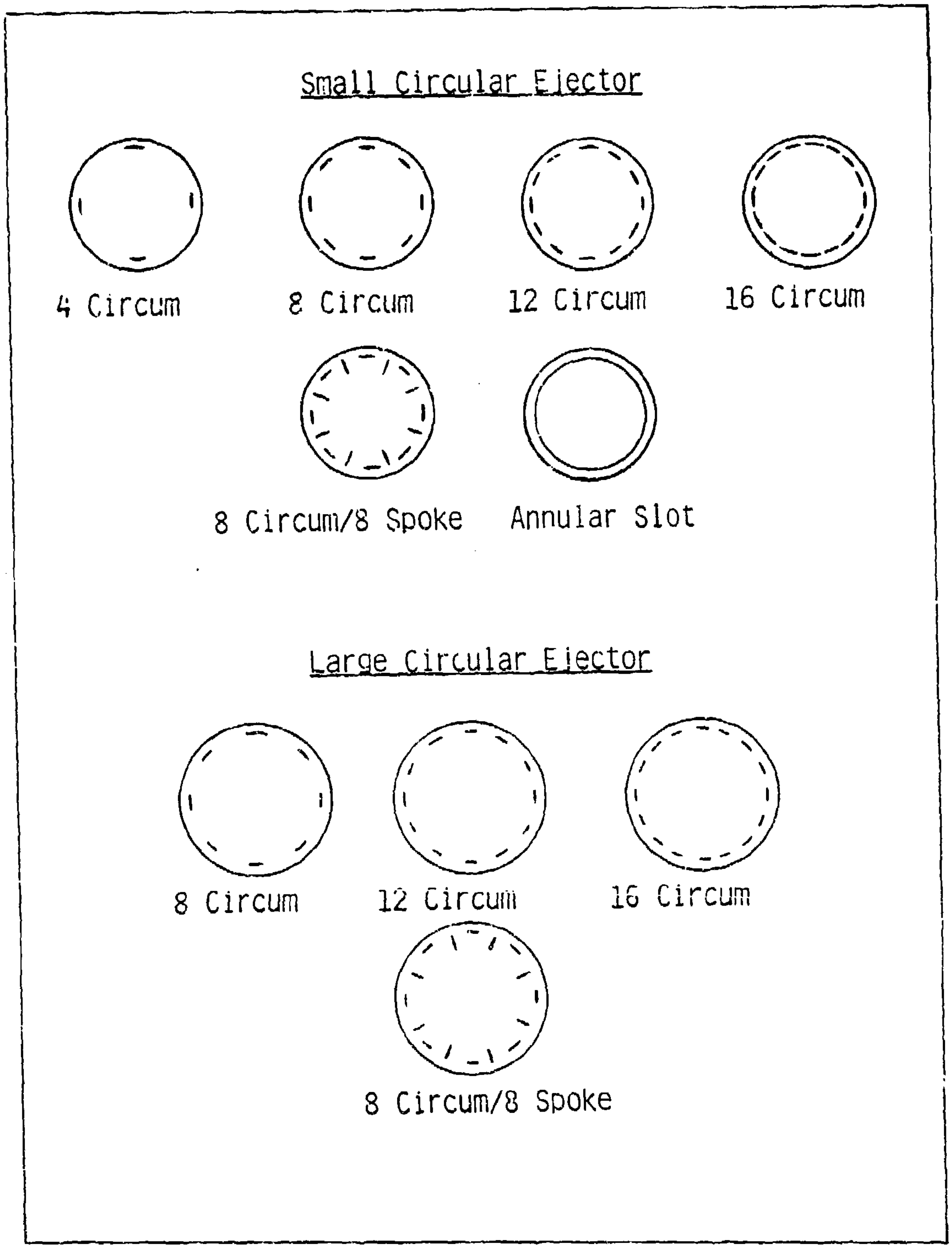


Figure 6. Nozzle Configurations Tested in Circular Ejectors

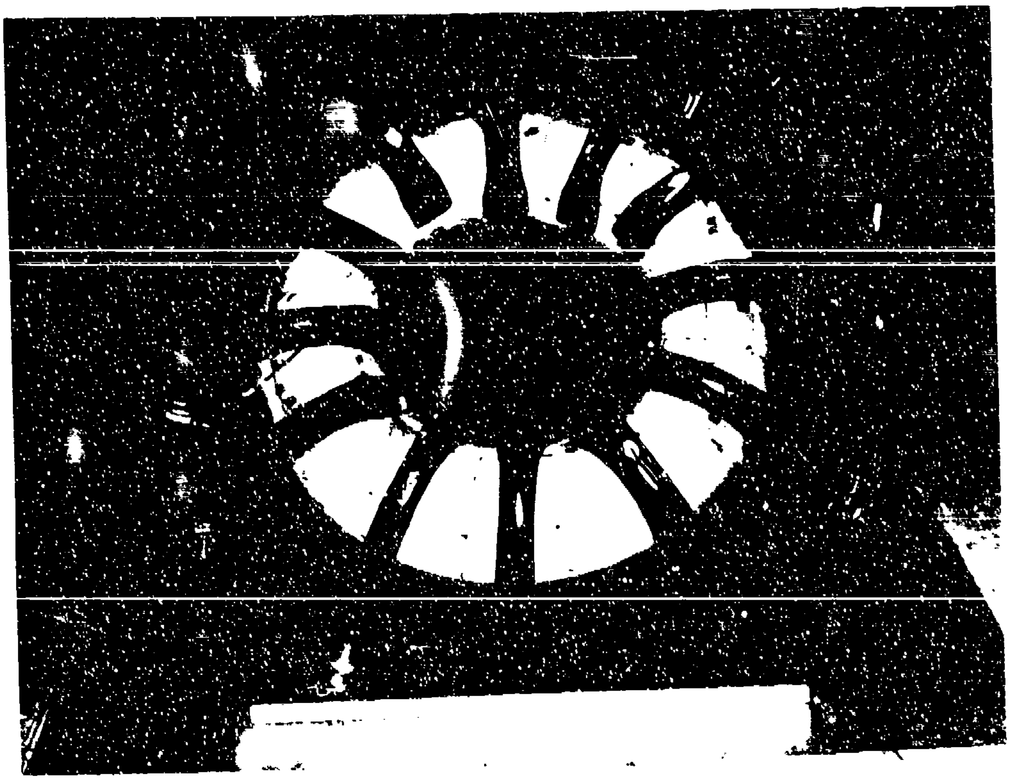


Figure 7. Large Circular Ejector with Twelve Circumferential Nozzles Installed

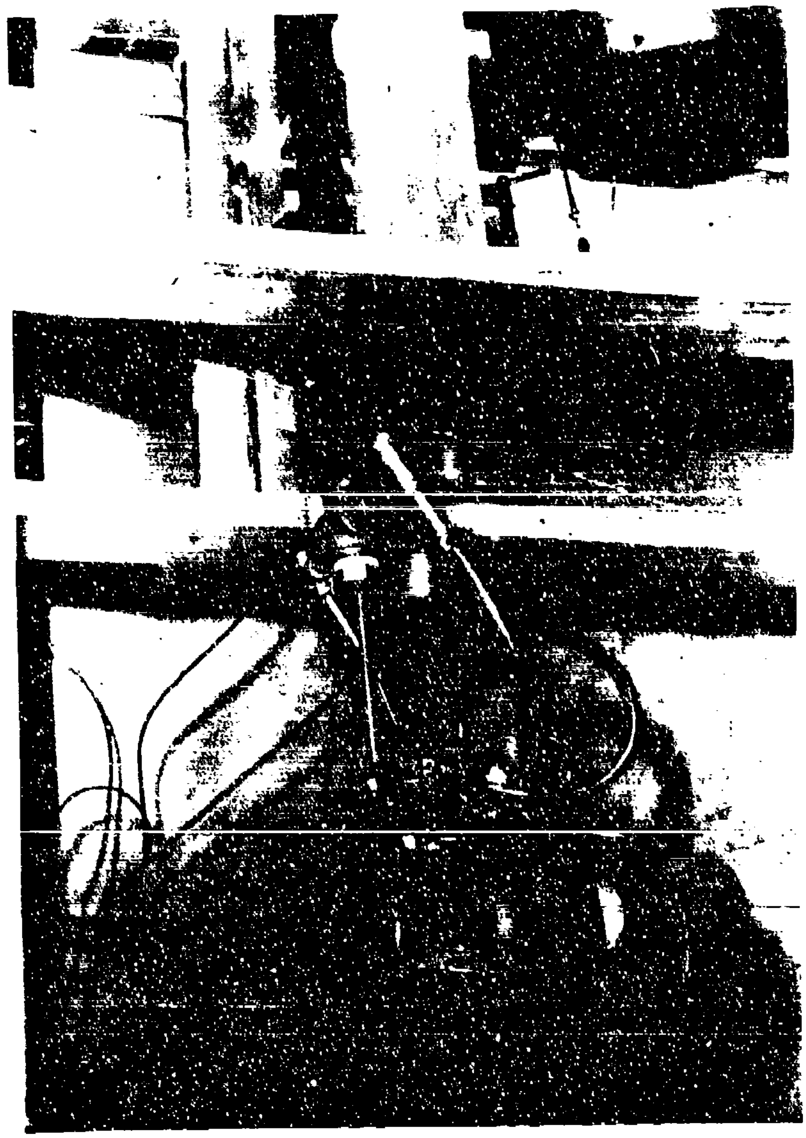


Figure 8. Photograph of Test Stand with Circular Ejector

Figure 9. Photograph of Thrust Calibration Ring

Other Components

Other test equipment used during this study included a "BLH Electronics Model 100 P" strain indicator, a micrometer (used to measure nozzle slot dimensions), a set of standard weights which were calibrated to ±1 mg/500 mg, standard manometer boards (both mercury and water), a pitot tube "rake" (used to take total pressure readings at the diffuser exit, (Fig 10) and a hand-held slender rod tipped with cotton thread. This rod was used occasionally for flow visualization of primary jet interactions and diffuser stall.

Comparison of Predicted and Experimental Performance

Using one-dimensional, incompressible fl w analysis, thrust augmentation can be calculated as a function of inlet area ratio, diffuser area ratio and assumed flow losses. Computations are normally accomplished with the aid of a large digital computer and often involve interactive methods. Huang and Kisielowski (Ref 6), numerically calculated thrust augmentation values for various ejector configurations. Their results are presented in the form of nomographs for a wide range of operating conditions. These nomographs provide a relatively simple yet effective means of predicting thrust augmentation characteristics of ejectors during preliminary design.

Test data from the initial confidence runs, made to determine repeatability of earlier data, were fitted to performance curves predicted by Huang and Kisielowski's

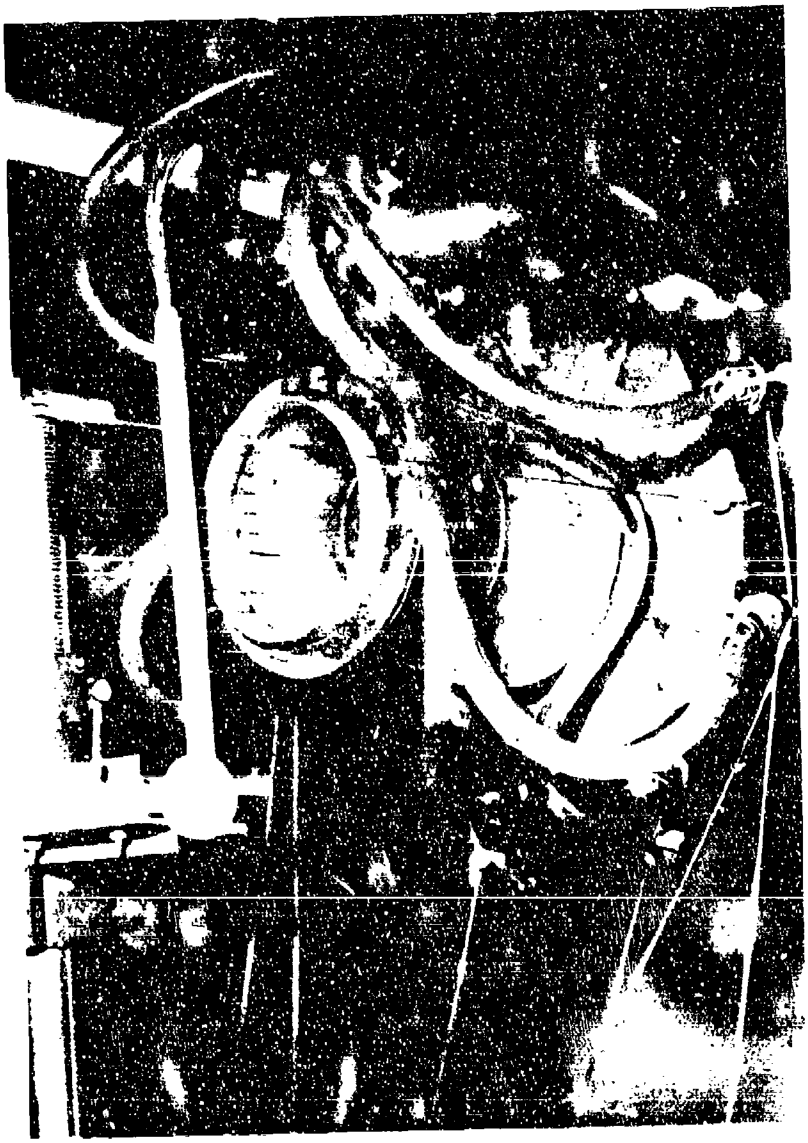


Figure 10. Photograph of Pitot Tube Rake

nomographs. This correlation of data allowed flow losses to be estimated. The assumed flow losses were used to predict the performance of all subsequent test configurations. The following flow losses were assumed for the rectangular ejector; inlet loss factor - 10 percent, mixing chamber loss factor - 5 percent, diffuser loss factor - 10 percent. For the circular ejector assumed flow losses were; inlet loss factor - 5 percent, mixing chamber loss factor - 3 percent, diffuser loss factor - 10 percent.

III Results and Discussion

Rectangular Ejector

The Kedem designed rectangular ejector, with dual primary nozzles, was tested to insure repeatability of previously obtained data. Thrust augmentation values, corrected for a variation in primary nozzle dimensions were repeated within 4 percent of values previously cited. The influence of diffuser exit area ratio (A_3/A_2) on thrust augmentation is presented in Fig 11. A velocity profile, as measured at the diffuser exit, is presented for a typical test run (Fig 12). The above data was used for comparing the effect of hardware modifications made to the original design.

Influence of Mixing Plates. Knife edge aluminum plates were installed at the mixing chamber inlet plane, approximately 0.95 in from the primary nozzles and 0.5 in from the end walls. Tests were made to determine the effect of these plates on mixing and thrust augmentation. The velocity profile for this configuration was significantly flattened (Fig 13) indicating increased mixing; however, thrust augmentation was reduced from 1.4 to 1.08. Besides an increase in audible noise, the plates created turbulent mixing at the inlet. Swirling of a cotton thread "tuft", used for flow visualization, indicated that vortices were developed at the leading and trailing edges of the plates. It appears that any benefits that may have resulted from increased mixing were countered by the

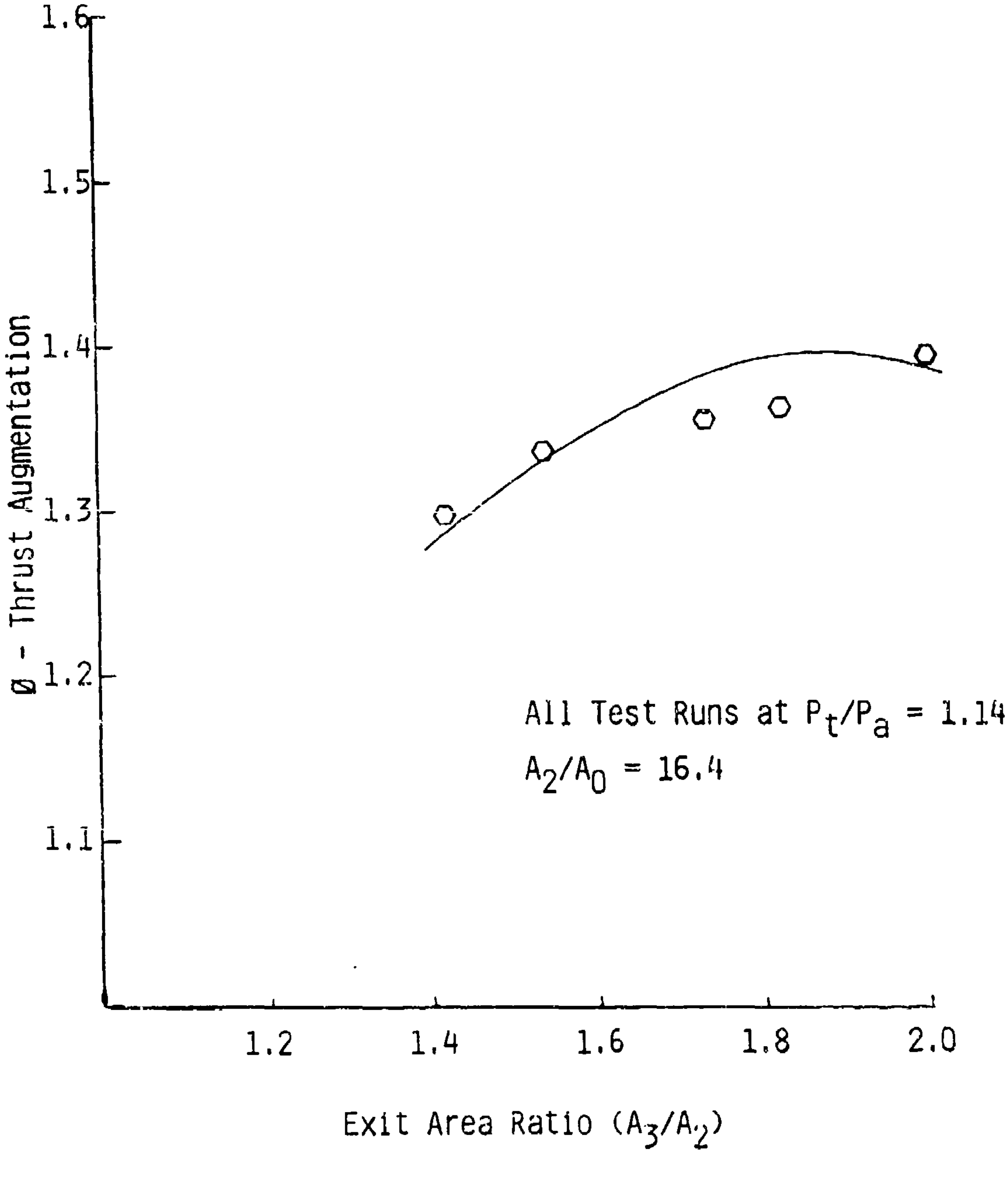


Figure 11. Performance of Rectangular Ejector - Original Design

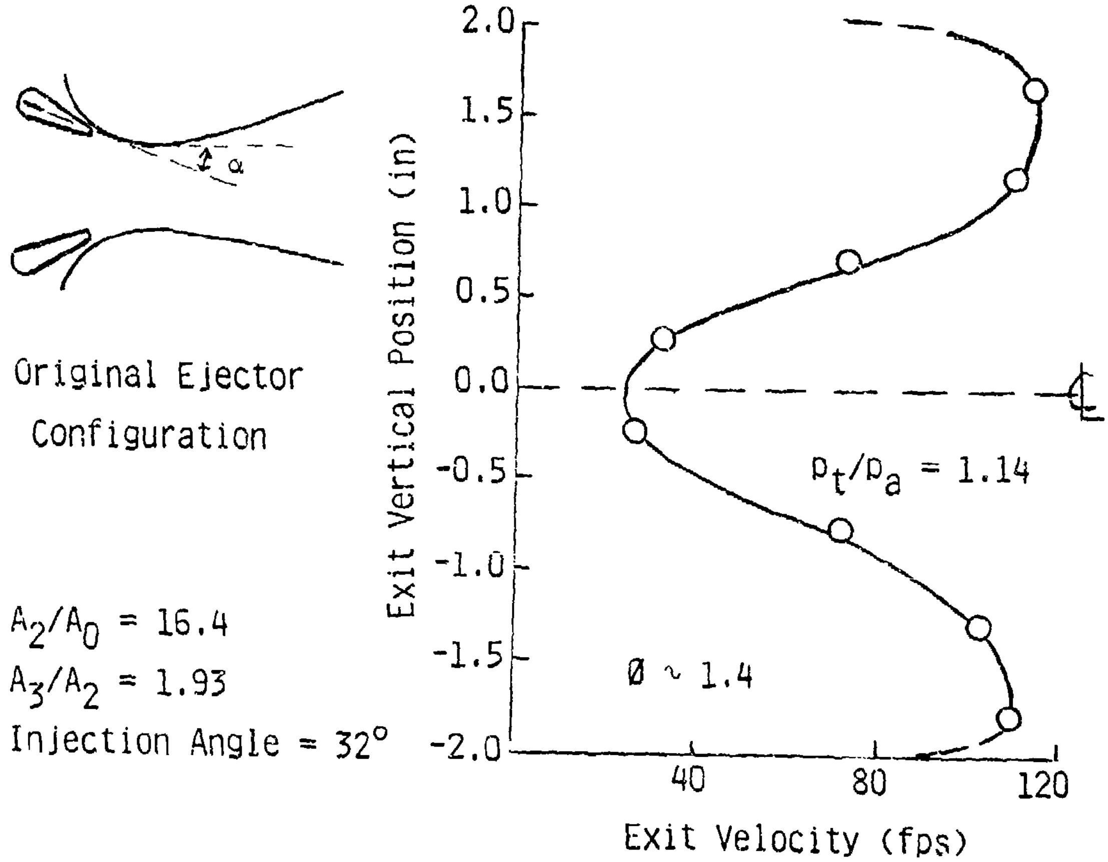


Figure 12. Original Rectangular Ejector Velocity Profile

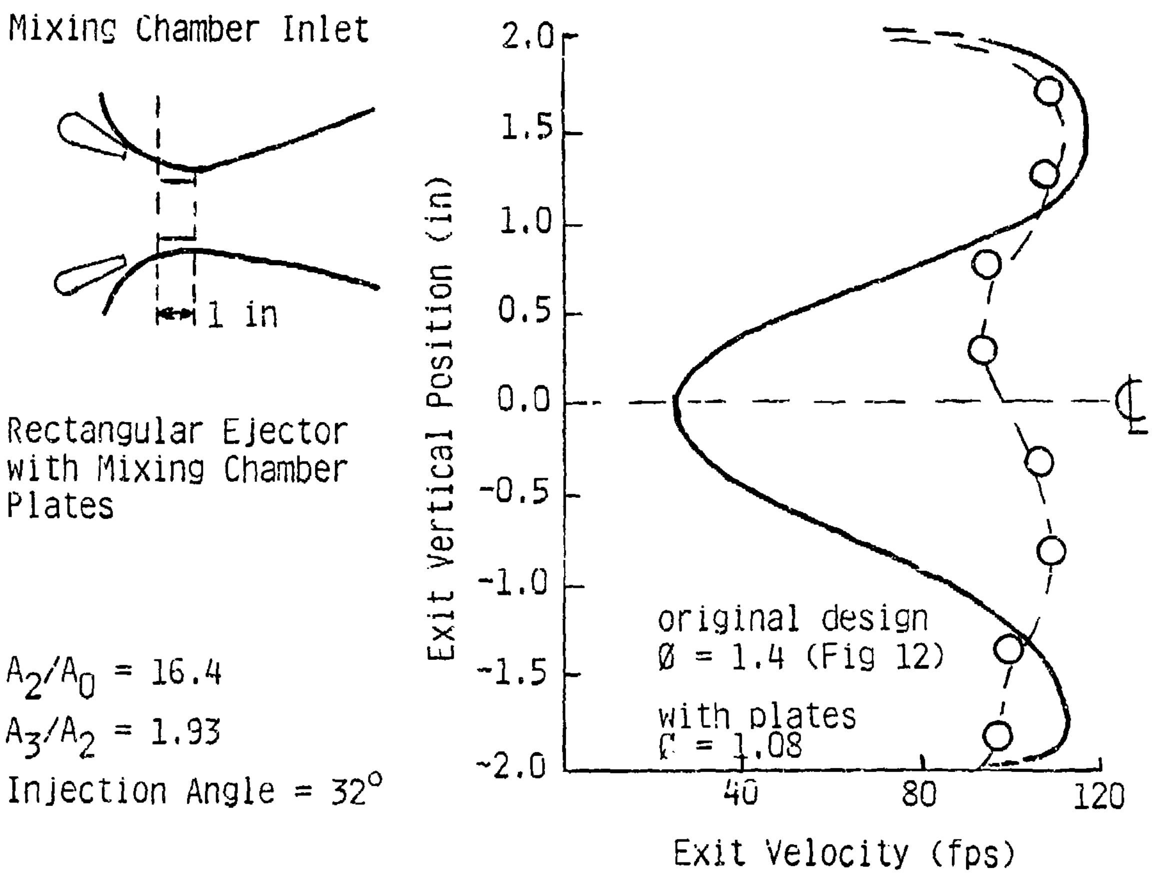


Figure 13. Influence of Mixing Chamber Plates on Exit Velocity Profile

dissipative effects of these vortices and the increased drag of the plates. The aluminum plates were also positioned in the diffuser section. This configuration was similar to the guide vanes installed and tested by Moore and Kline (Ref 9) in a two-dimensional diffuser and the splitter places configuration tested by Yang (Ref 10) during a study of circular diffusers. When diffuser plates were installed in the rectangular ejector, thrust augmentation was reduced. For a zero degree angle of attack, the plates increased mixing, but drag effects reduced thrust augmentation by 10 percent. When the angle of attack was increased, Ø was further reduced. A typical configuration is shown in Fig 14.

Unlike the configurations tested by Yang, the ejector inlet flow was non-uniform, with the highest flow velocities near the end walls. It appears that the plates disturbed this high energy fluid by creating turbulence and directing the flow towards the centerline. Exit velocity profiles were flattened but at the expense of reducing the high energy flow near the diffuser end walls. This additional deceleration of fluid near the end walls decreased diffuser efficiency and thrust augmentation.

With the plates removed, the ejector was tested using the modified nozzles with inserts, discussed in Section II. This configuration increased mixing and thrust augmentation (Fig 15). Maximum Ø increased 11 percent as compared to the original design, 1.4 to 1.58. A comparison of the modified ejector's performance is presented in Fig 16.

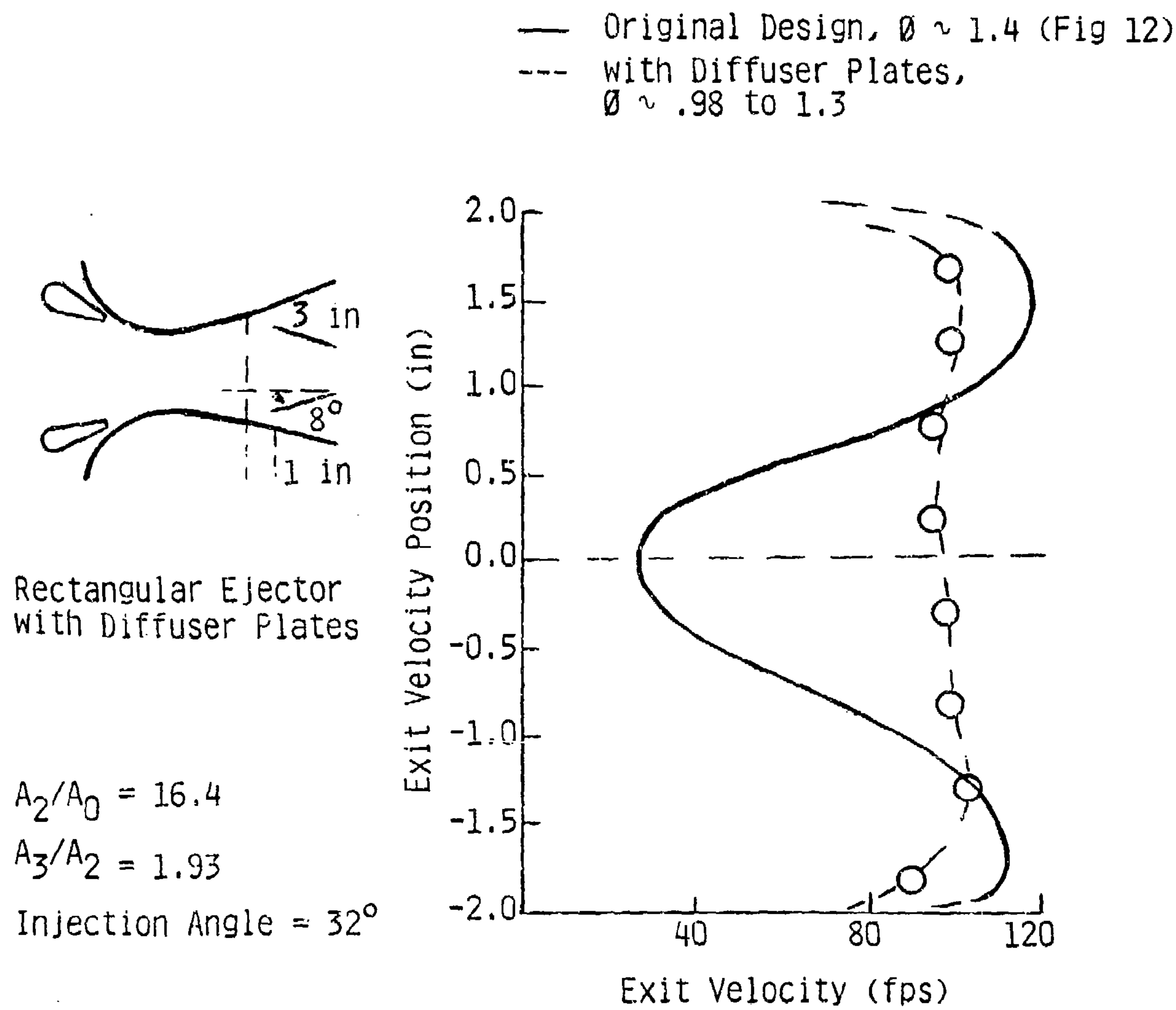


Figure 14. Influence of Diffuser Plates on Exit Velocity Profile

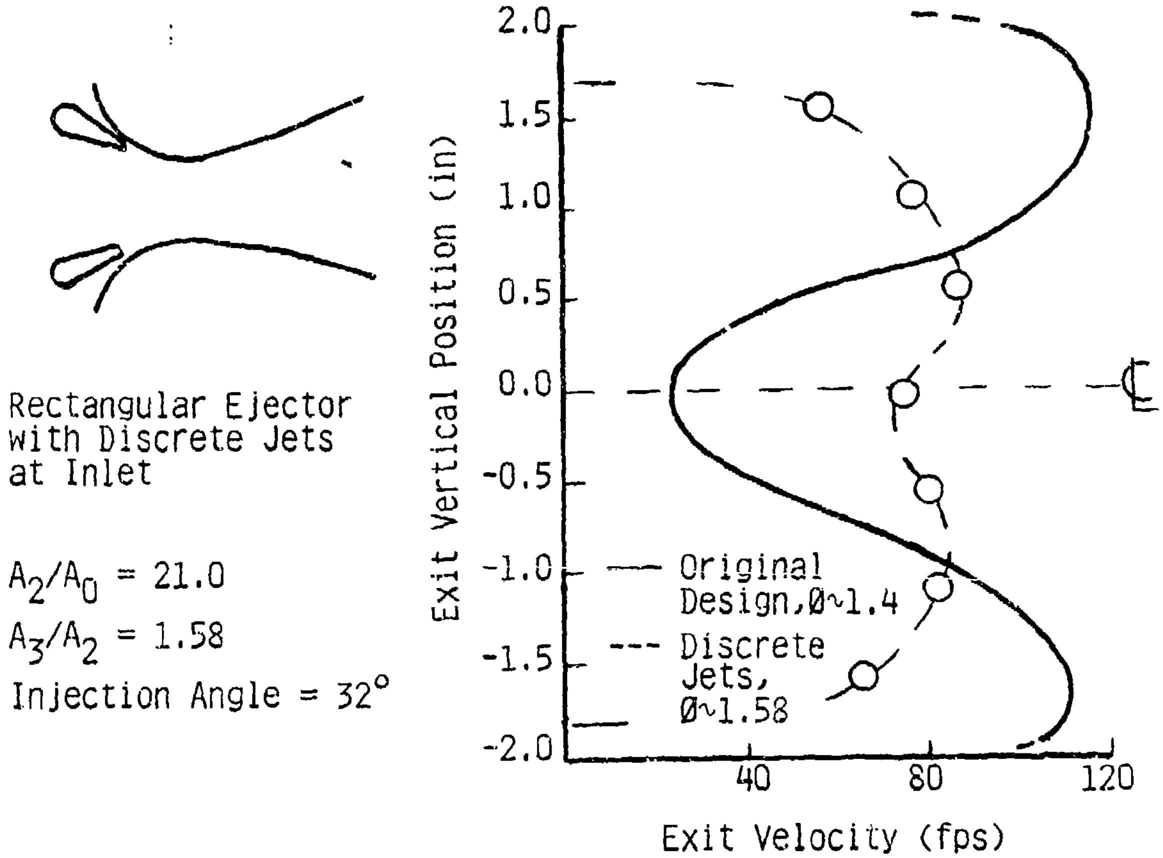


Figure 15. Influence of Discrete Jets at the Inlet on Exit Velocity Profile

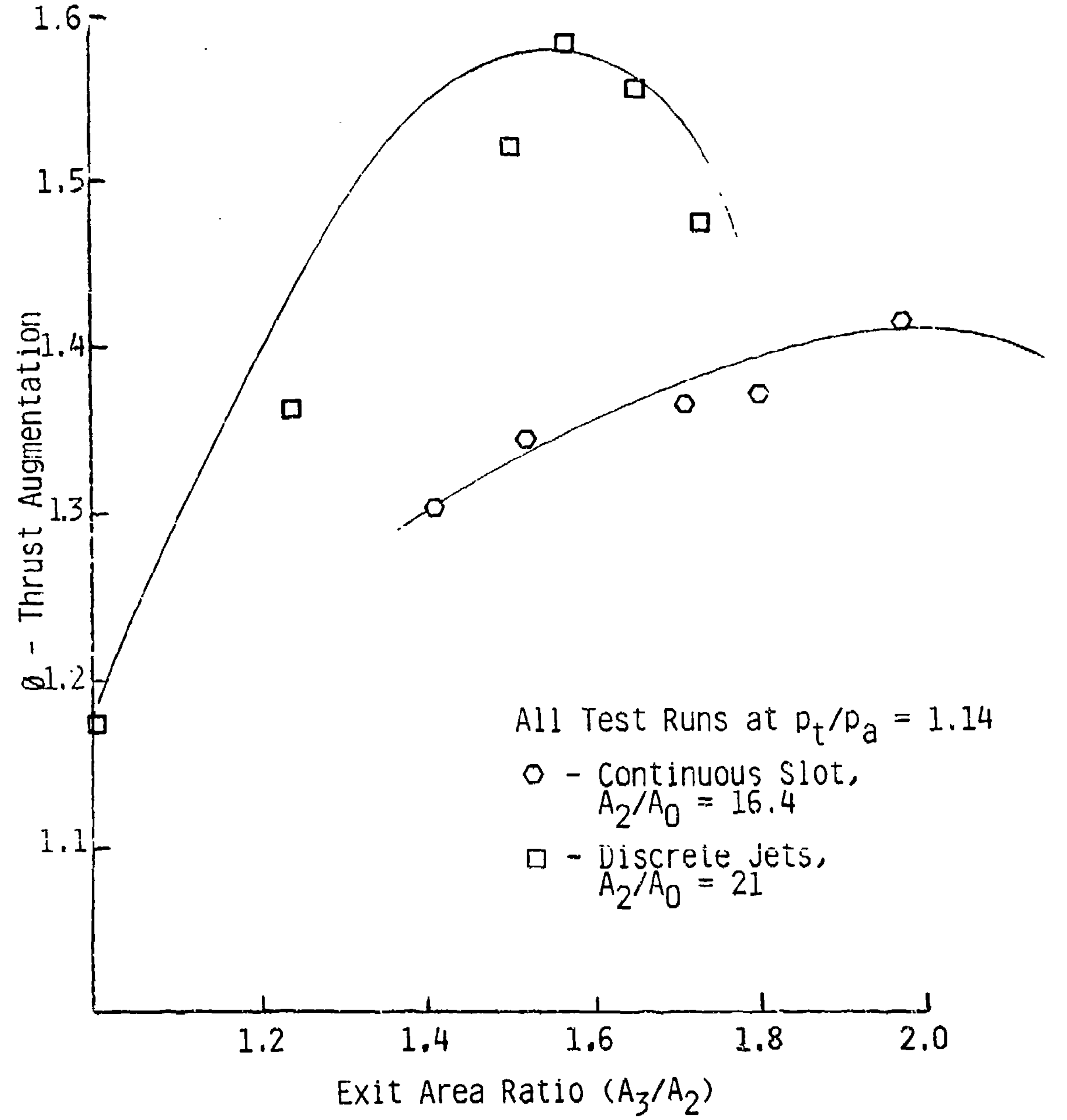
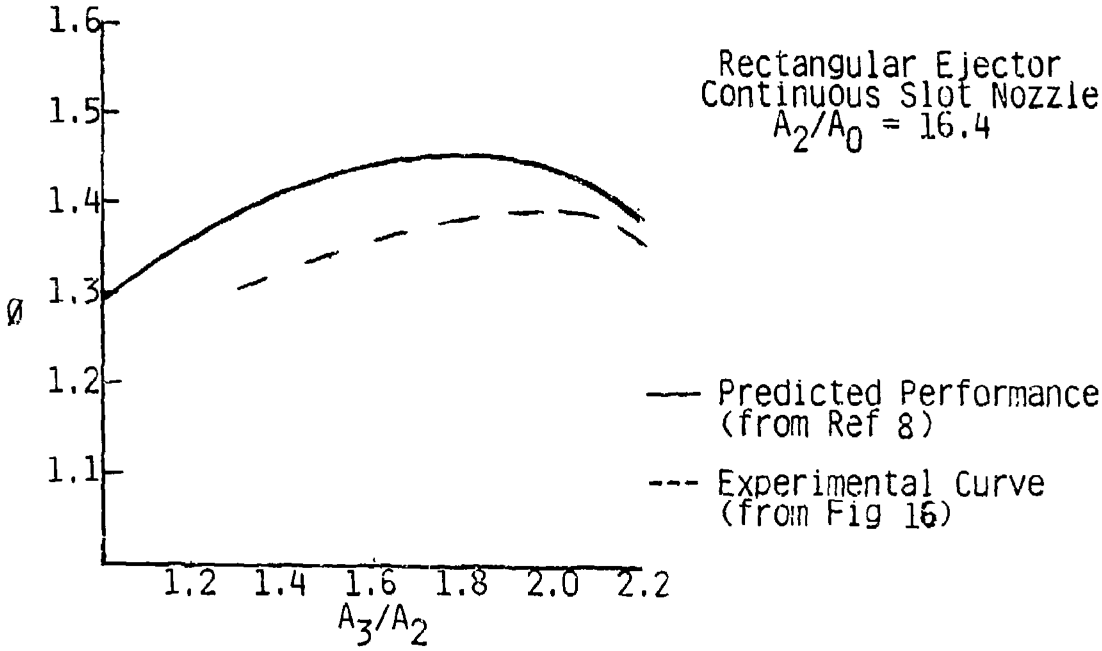


Figure 16. Performance of Rectangular Ejector With Continuous Slot and Discrete Jets

Influence of Geometry. As indicated by Figure 16, thrust augmentation increased with increases in diffuser area ratio. Maximum values of ϕ occurred at 1.93 for the continuous slot nozzle and 1.58 for the modified nozzles. These results agree with previous studies regarding the effects of diffuser area ratio, specifically, Fancher (Ref 11) and Quinn (Ref 12).

One-dimensional flow analysis predicts increases in ϕ with increases in inlet area ratio, A_2/A_0. As predicted ϕ_{max} also increased, from 1.4 to 1.58. This trend is discussed in detail by Salter (Ref 13) and Huang and Kisielowski.

Influence of Discrete Jets. Huang and Kisielowski nomographs, discussed earlier, were used to predict the thrust augmentation characteristics of the modified nozzles. Since the outer dimensions of the nozzles remained constant, flow losses were assumed to be the same as the original designed ejector. Figure 17 compares the predicted and experimental curves for both ejectors. Thrust augmentation for the eight discrete jets configuration was higher than predicted by the nomographs, 1.58 versus 1.49. Also, this configuration was more sensitive to increases in diffuser area ratio than predicted. Stall occurred at a diffuser area ratio of 1.75 versus a predicted value of approximately 1.9. Improved mixing of the primary and secondary fluids increased ϕ_{max}, but the subsequent decrease in flow velocity near the diffuser walls resulted in earlier diffuser stall.



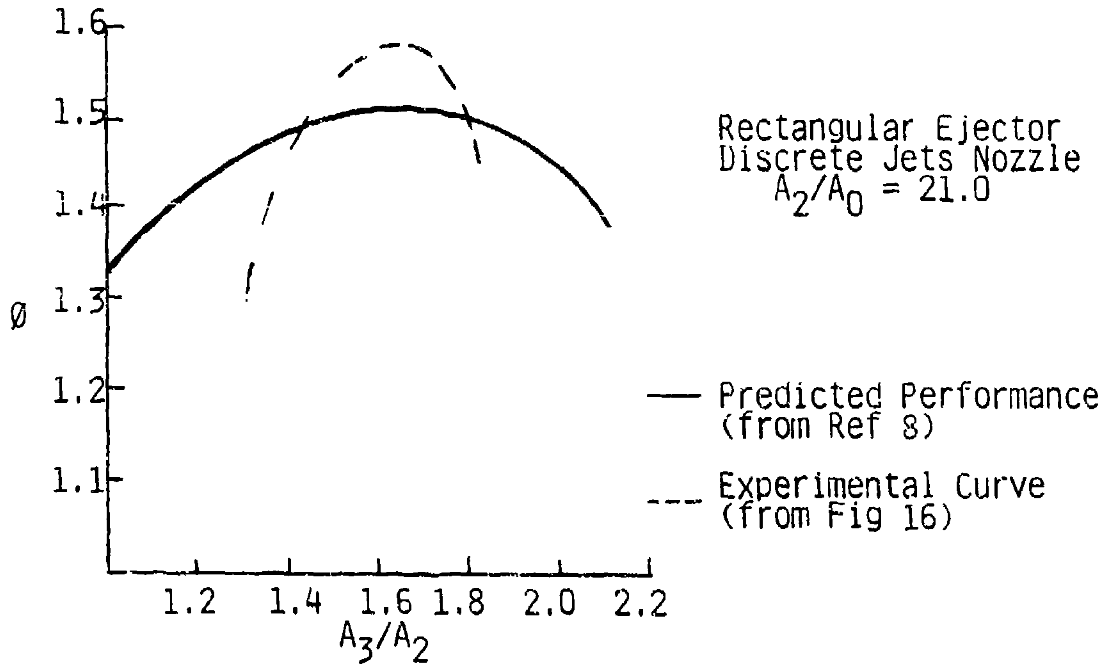


Figure 17. Predicted Performance and Experimental Curves for Rectangular Ejector

Circular Ejectors

The influence of primary nozzle configuration, inlet area ratios and diffuser geometry were tested using two circular axisymmetric ejectors and four types of primary nozzles. The primary nozzle thrust efficiencies ranged from 94 percent to 98 percent (Appendix C provides detailed information). Tests were also conducted to determine the influence of fluid injection angle on thrust augmentation.

Small Ejector. The original eight circumferential nozzles were tested to insure repeatability of data obtained in an earlier investigation (Ref 5). Thrust augmentation values were within 2 percent of those previously cited. The influence of diffuser exit ratio on thrust augmentation is presented in Fig 18. The ejector performance increased as diffuser area ratio increased up to a maximum diffuser area ratio of 2.9. This trend is predicted by one-dimensional analysis and agrees with the experimental results of Alperin and Wu (Ref 14), where high diffusion rates of A_3/A_2, 2.4 were reported. Symmetric configurations of 4, 12 and 16 circumferential nozzles were also tested (Fig 19). The 4 nozzle configuration stalled for all diffuser sections tested. Thrust augmentation for the 4 nozzle configuration was approximately 1.2 when a "mixing chamber only" configuration was tested. The 12 and 16 nozzle configurations followed a general trend of increasing performance with increasing diffuser exit area ratio. All configurations stalled at area ratios greater than 2.9.

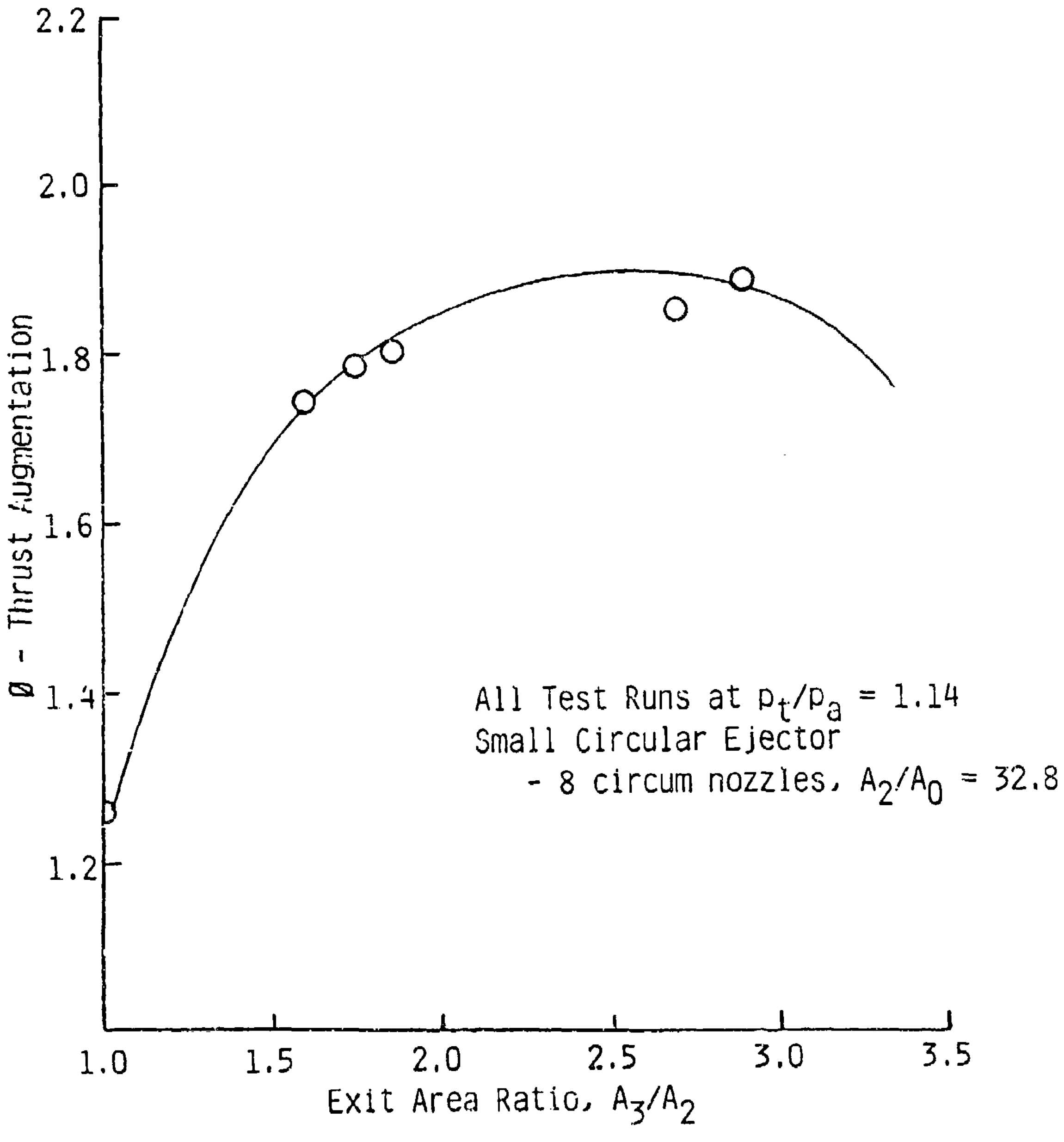


Figure 18. Small Circular Ejector Performance -
8 Circumferential Nozzles

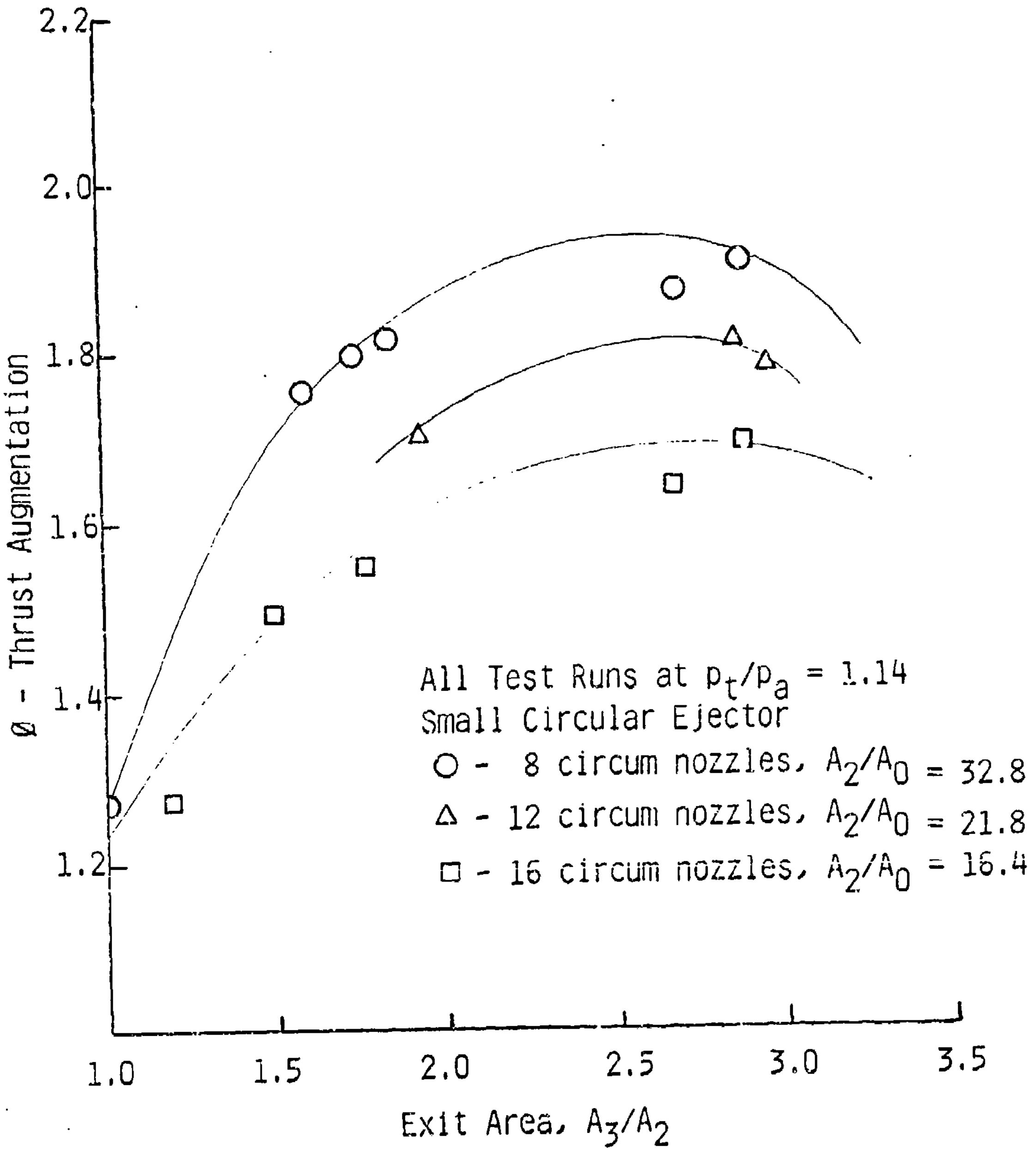


Figure 19. Small Circular Ejector Performance - 8, 12 and 16 Circumferential Nozzles

Testing was also accomplished using an annu r slot nozzle (Fig 20). This nozzle had the lowest inlet area ratio tested, 12.7; however, its performance was higher than the 16 circumferential nozzle, whose inlet area ratio was 16.4. Finally, the modified spoke nozzles, previously described, were tested in combination with eight circumferential nozzles (Fig 21). Thrust augmentation was reduced significantly, when compared to the 8 circumferential nozzles acting along. Possible causes for this lower performance include the difference in inlet area ratio, and that the nozzles drag was still significant when compared to the circumferential nozzles.

Large Ejector. Configurations of 8, 12, and 16 circumferential nozzles were tested on the large ejector. Results are shown in Fig 22. Again a general trend of increased performance with increased exit ratio was followed. The 8 nozzle configuration performed well at low diffuser ratios but stalled at a ratio of 2.0. The 12 and 16 nozzle configurations followed the results of the small ejector. $\emptyset$ increased to a maximum at $A_3/A_2 \sim 2.9$ with stall occurring for higher ratios. Nozzle spacing appeared to be a significant parameter for these configurations and is discussed later. A combination of 8 circumferential and 8 spoke nozzles was tested (Fig 23). Again the circumferential nozzles acting alone gave superior thrust augmentation values.

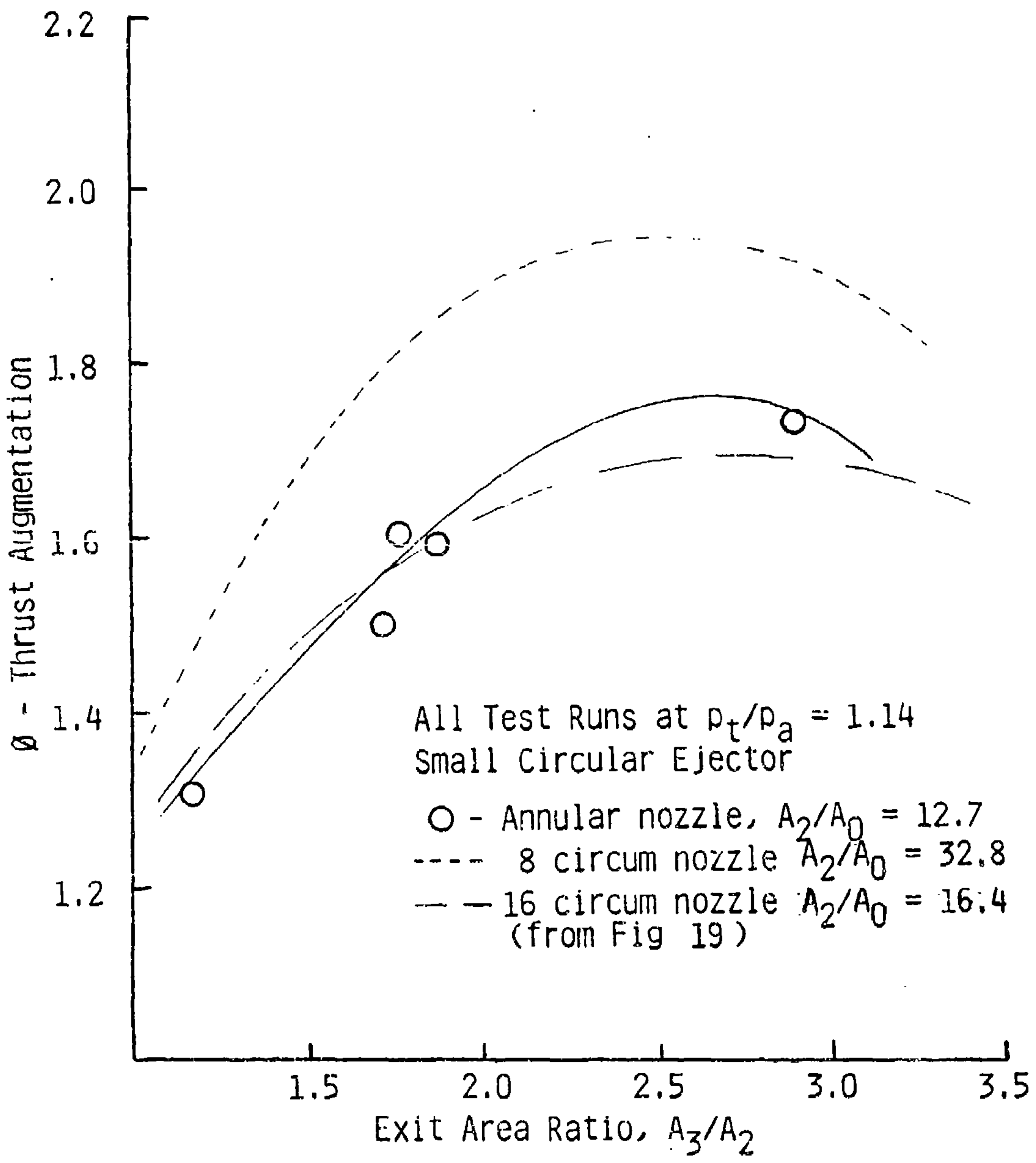


Figure 20. Small Circular Ejector Performance - Annular Slot Nozzle

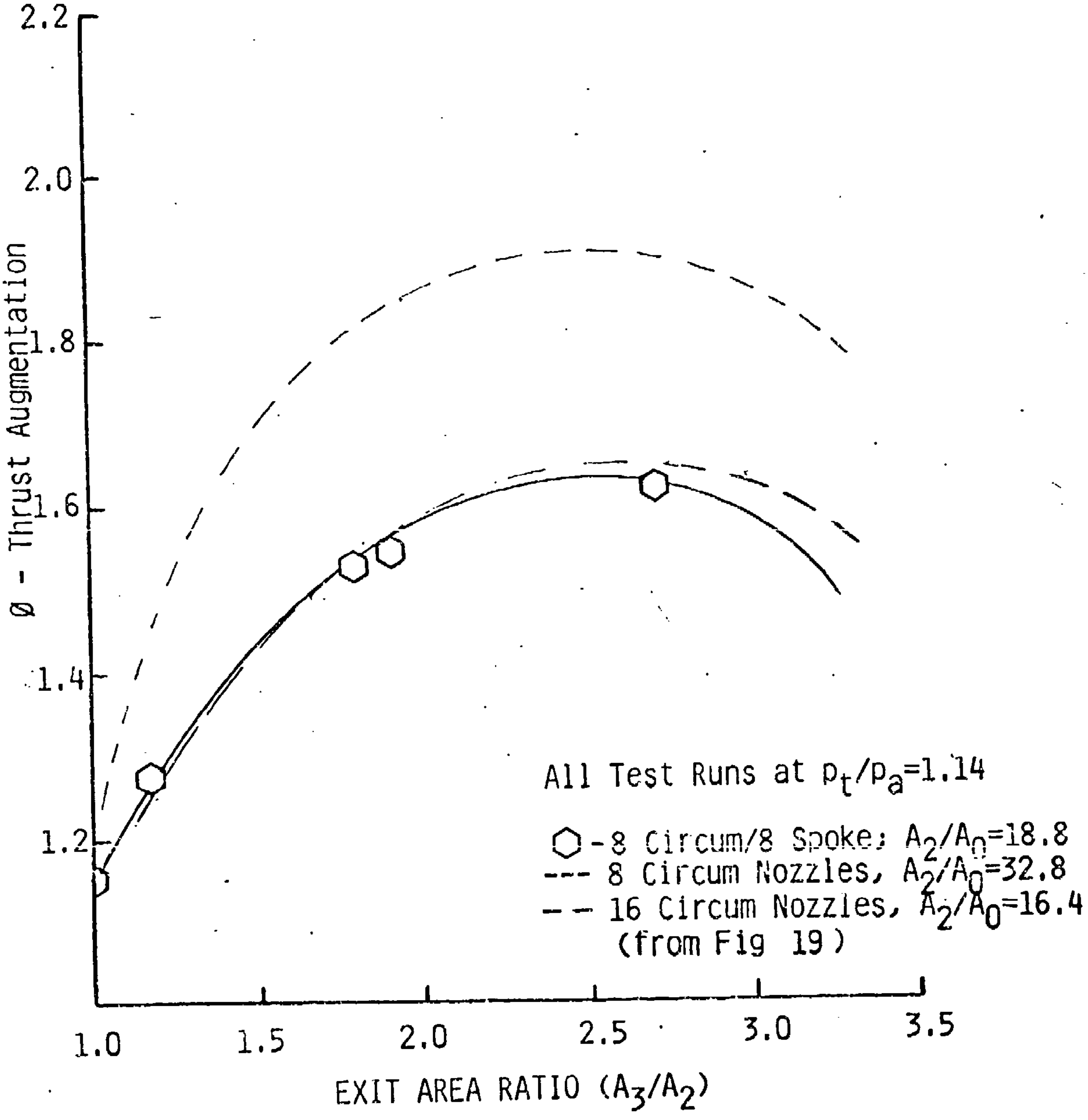


Figure 21. Small Circular Ejector Performance With 8 Circum/8 Spoke Nozzles

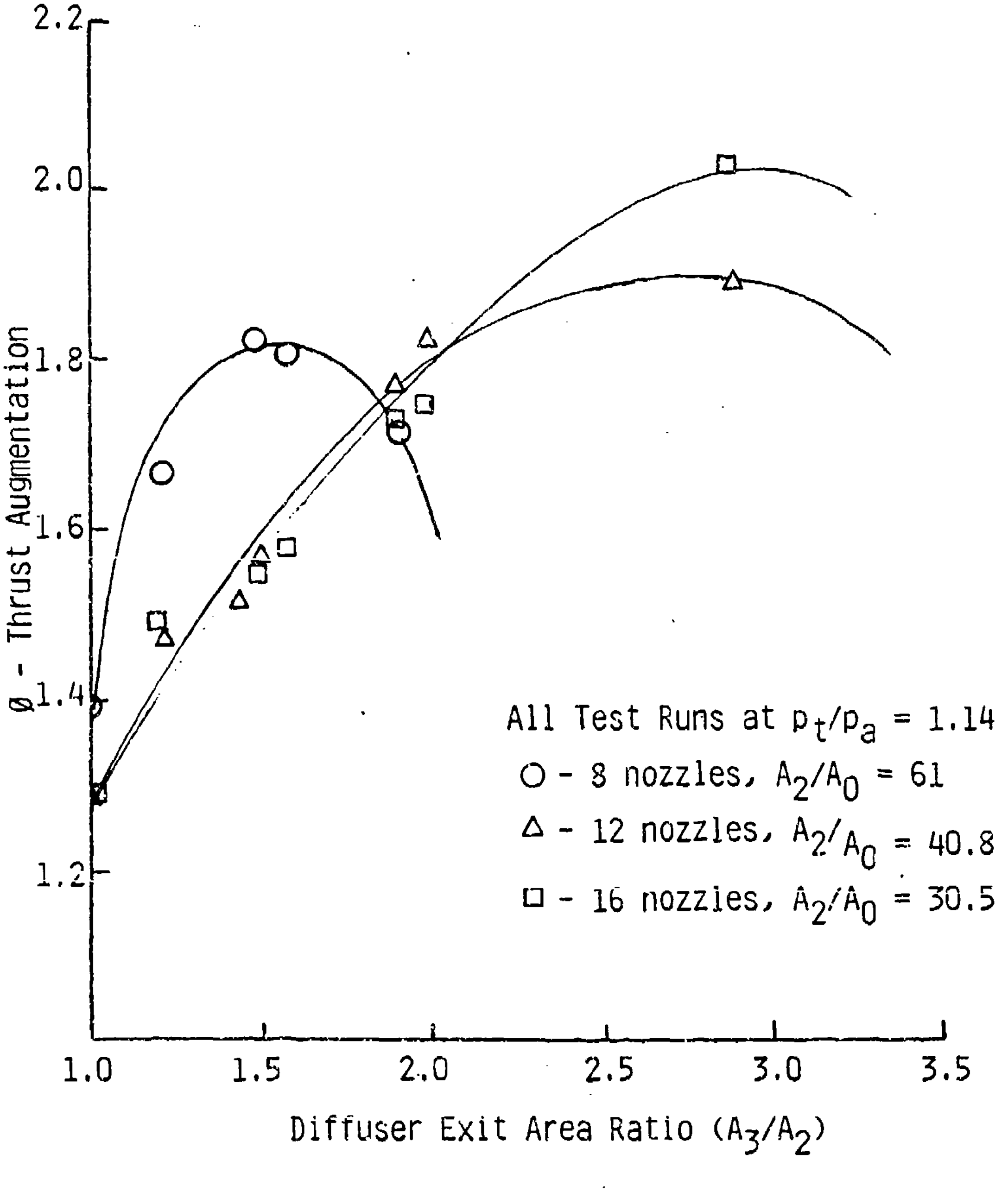


Figure 22. Large Ejector Performance Using Circumferential Nozzles

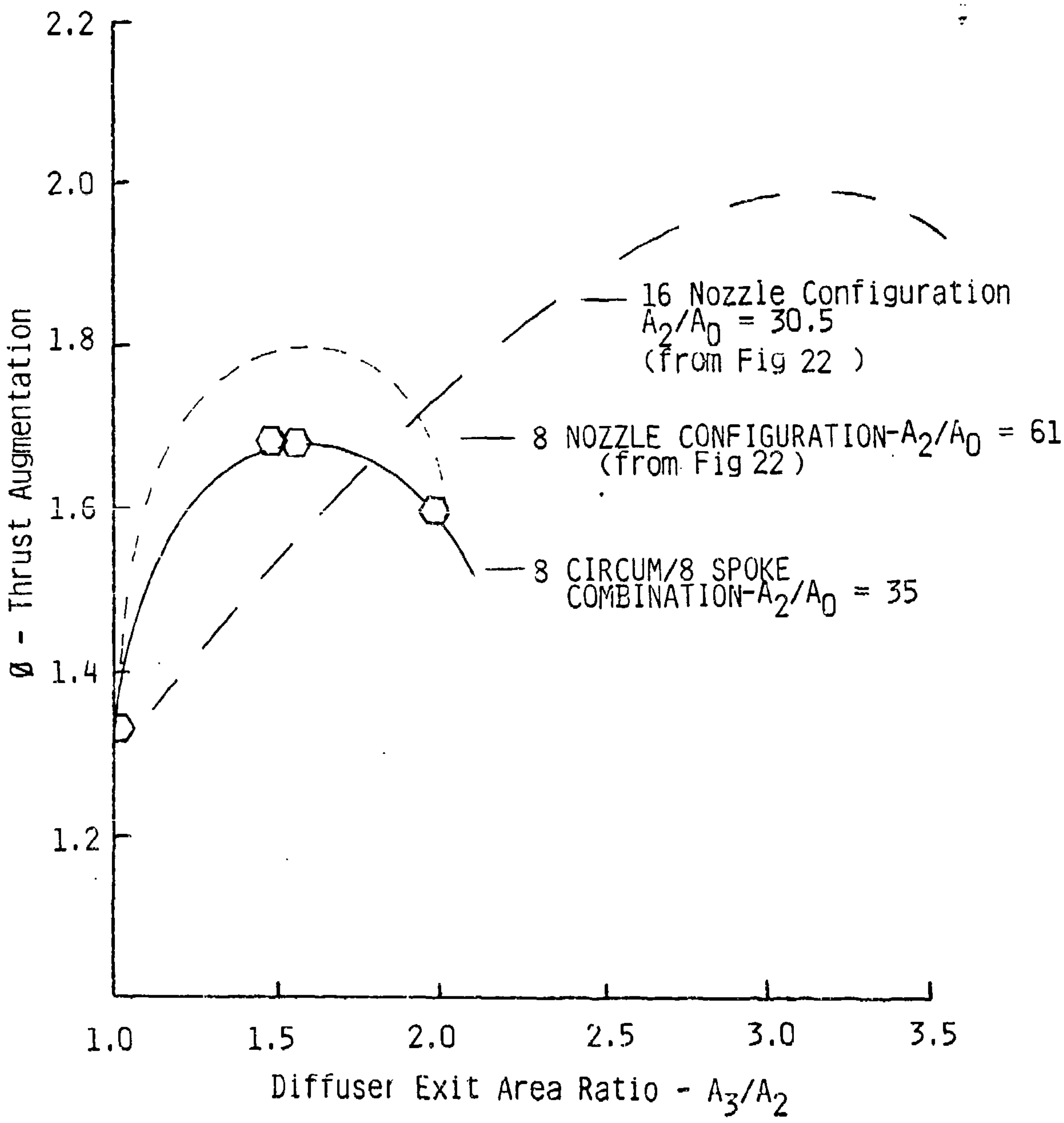


Figure 23. Large Ejector Performance Using 8 Circumferential/8 Spoke Nozzles

Influence of Inlet Area Ratio. Huang and Kisielowski nomographs were used to compare the experimental results of the circular ejectors. Figures 24 and 25 present the predicted curves and the experimental curves for all configurations tested. The predicted trend of decreasing Ø with decreasing inlet area ratio is followed by the small ejector for all diffuser area ratios. The trend is also followed by the large ejector up to exit area ratios of approximately 2.0, where a reversal occurs. As the number of nozzles increased, the benefits of maintaining a high energy flow near the diffuser walls compensates for the decrease in inlet area ratio.

Influence of Discrete Nozzles. The torus nozzle configuration performed better than the 16 nozzle configuration on the small ejector (Fig 20). This was despite the fact that the torus nozzle had an inlet area ratio 29 percent smaller. This deviation from the predicted trend appears to be the result of the increased drag of the "wetted diameters" of the primary nozzles. Increases in drag due to an increase in "wetted diameters" of the primary nozzles is discussed by Quinn and by Alperin and Wu (Ref 15).

Thrust augmentation values for all configurations tested in this investigation were plotted for constant diffuser geometries and various nozzle spacings, h (Fig 26). When this distance, as measured along the inlet perimenter, is expressed as the percentage of inlet perimeter covered, an optimum "wetted" perimeter of 40 to 60 percent is found

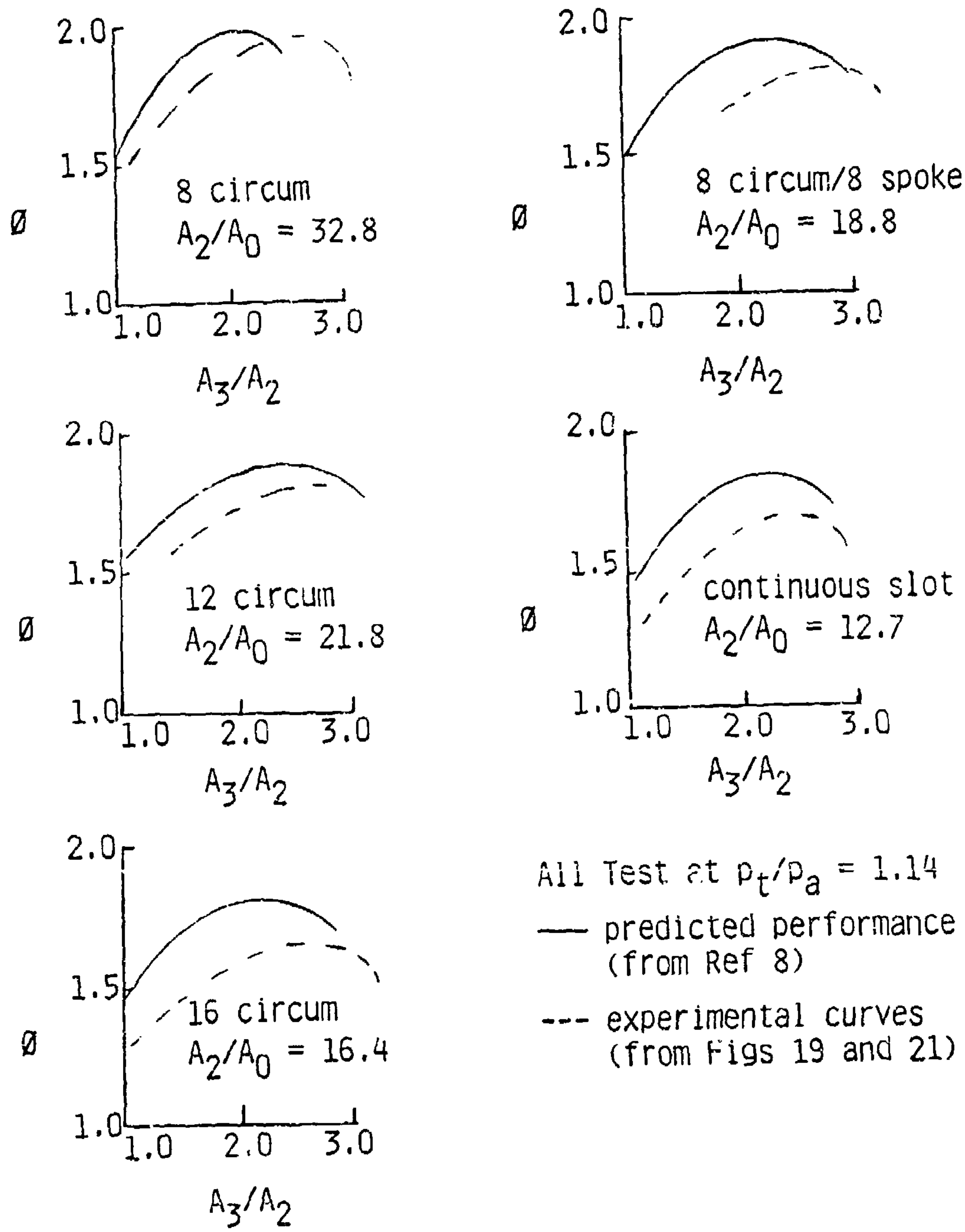


Figure 24. Predicted and Experimental Performance of the Small Circular Ejector

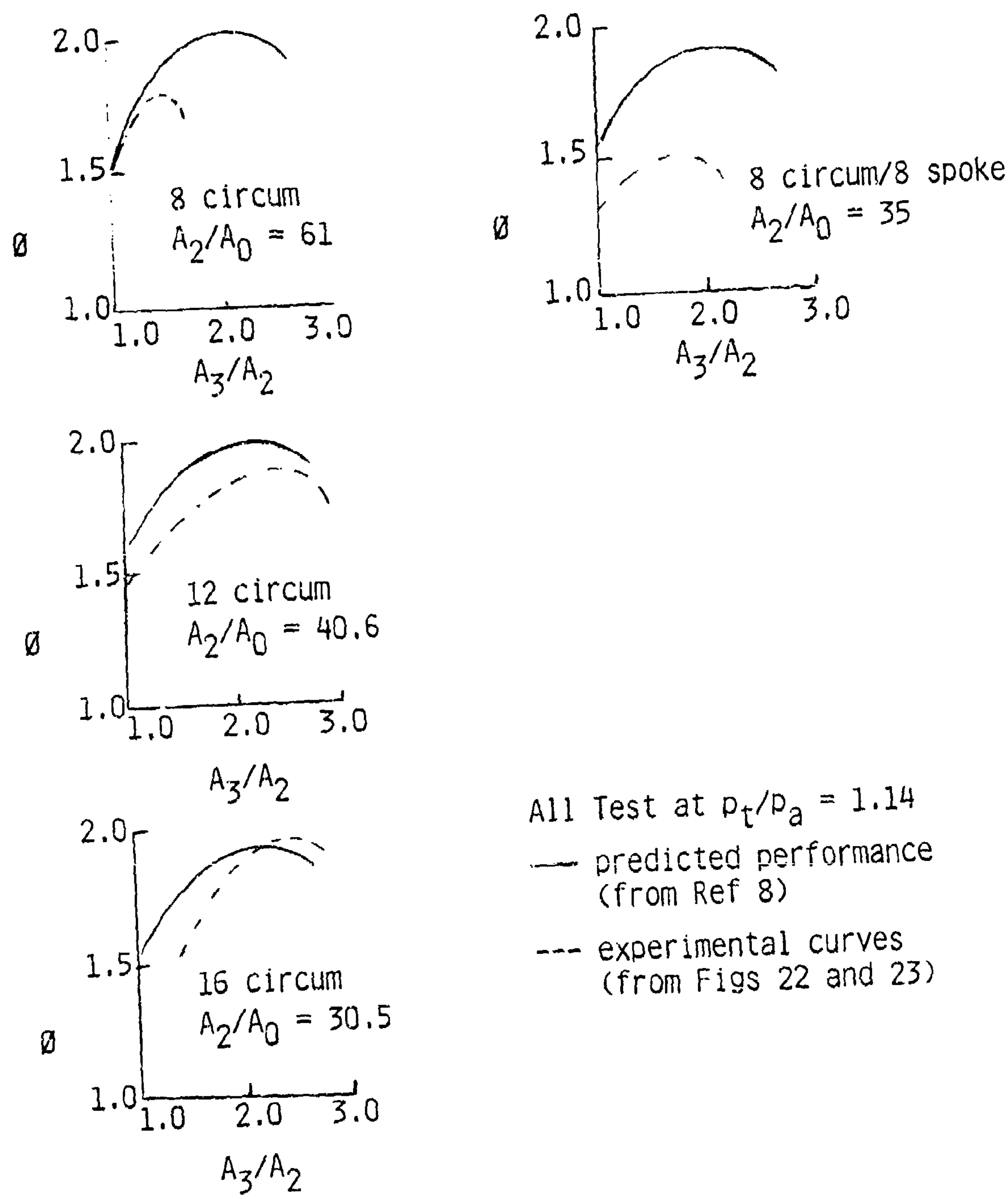


Figure 25. Predicted and Experimental Performance of the Large Circular Ejector

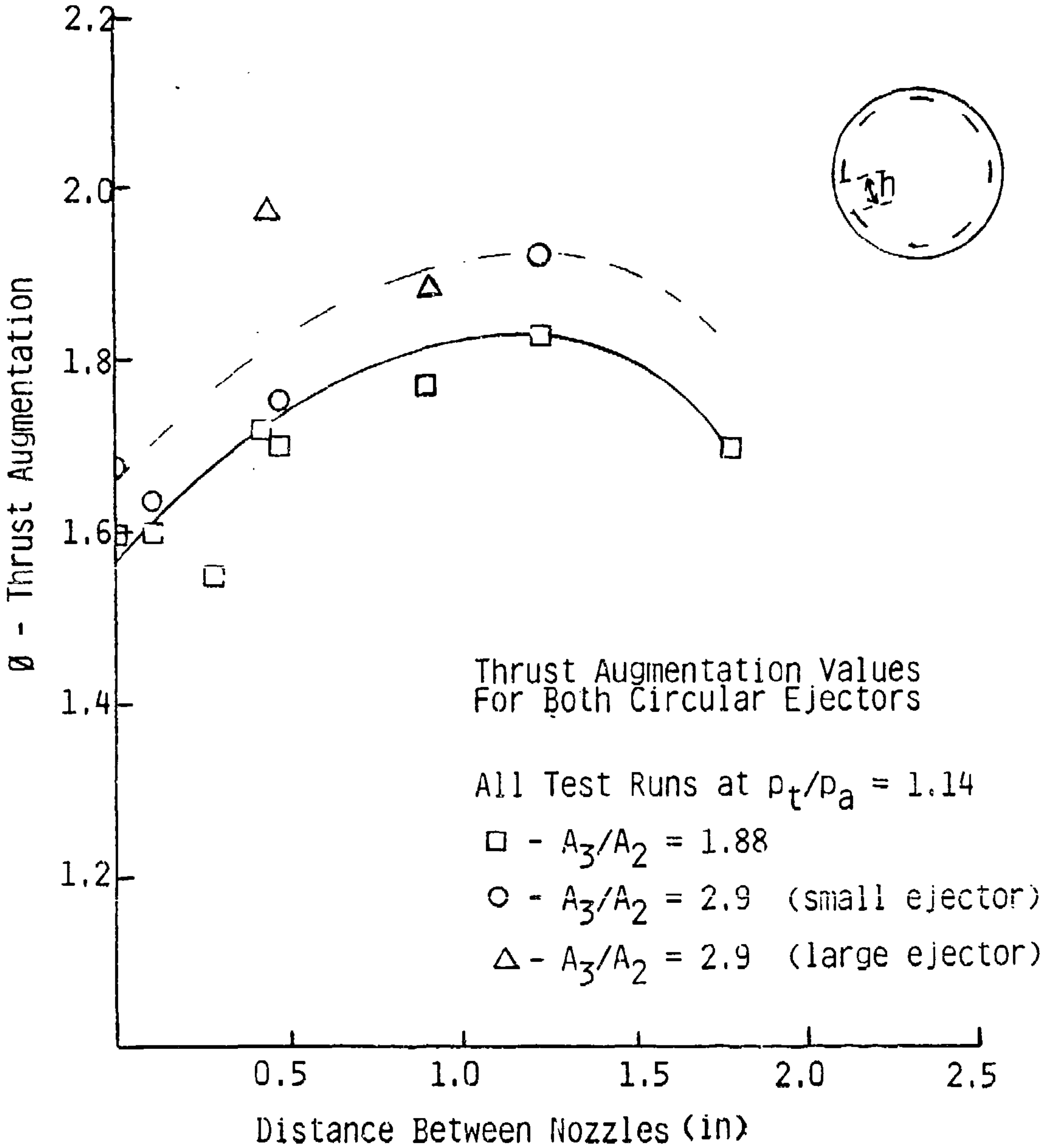


Figure 26. Influence of Nozzle Spacing on Thrust Augmentation

(Fig 27). This result is similar to Alperin and Wu's value of 42 percent and confirms Salter's discussion concerning the effects of nozzle spacing.

Influence of A_3/A_0. When all test data (Appendix B) is used to generate a plot of thrust augmentation versus the ratio of diffuser area to primary nozzle area, A_3/A_0, a trend is apparent (Fig 28). Following Fancher, an approximate relationship between ϕ (for unstalled configurations) and A_3/A_0 was determined. Using a linear regression program ϕ was found to be:

$$\phi \sim 1.25 + 0.007\ (A_3/A_0)$$

This function differs from Fancher's results, where

$$\phi \sim 1.75 + 0.025\ (A_3/A_0) \qquad \text{(from Ref 11)}$$

Fancher used center body primary nozzles and limited his investigation to inlet area ratios between 5 and 14. This investigation used primary nozzles which achieved Coanda type flow at the throat. Inlet area ratios were 16 to 61. Coanda flow increases secondary fluid entrainment and provides a "lip suction" at the inlet which increases ejector thrust. This difference may be the cause for the larger initial "ϕ intercept" values. The smaller influence of A_3/A_0 is predicted by Salter, Nagaraja (Ref 16) and others. Most numerical analysis programs predict large increases in ϕ with increases in A_2/A_0 from 1 to approximately 20.

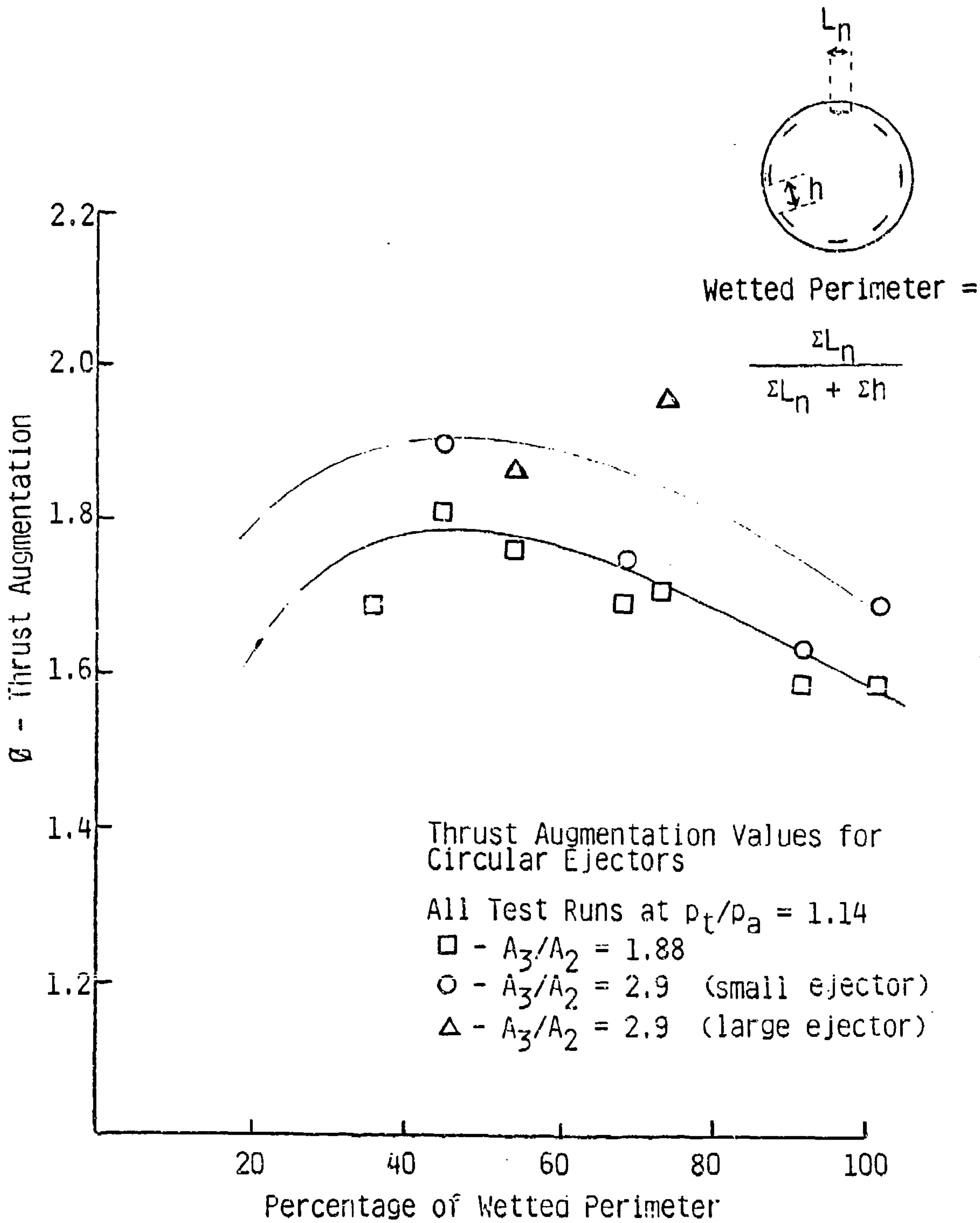


Figure 27. Influence of Wetted Perimeter on Thrust Augmentation

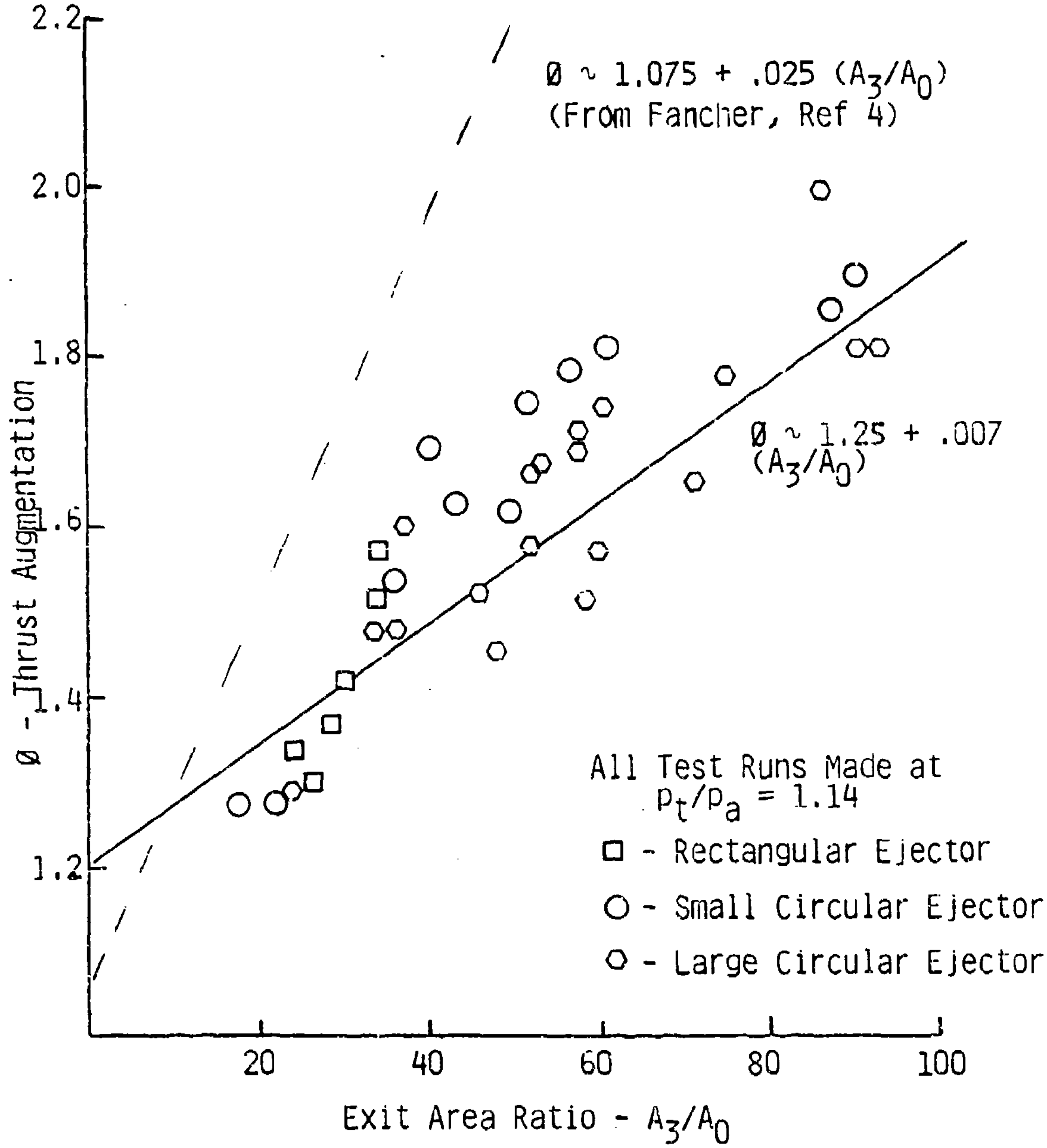


Figure 23. Comparison of All Ejector Data (Without Stall) as a Function of A_3/A_0

Effects of increasing A_2/A_0 above 20 are still beneficial, but the slope is generally lower. It is therefore not surprising that the ejector configurations tested in this investigation, $16 < A_2/A_0 < 61$, would have lower increases in $\emptyset$, when compared to Fancher's configurations of $5 < A_2/A_0 < 14$.

<u>Influence of Fluid Injection Angle</u>. The eight adjustable circumferential nozzles were placed at five discrete locations on the ejector's curved inlet. Fluid injection angle (α) was varied to determine the influence of location and injection angle on thrust augmentation (Fig 29). The results indicate that a primary consideration for Coanda type flow is that the injected fluid must enter the inlet tangent to the curved side walls. This conclusion is similar to the conclusions made by Alperin and Wu (Ref 16) and Reznick (Ref 5). In addition to this "tangency" condition, an optimum injection angle of 20 degrees was determined. This optimum angle was used for the majority of the ejector tests.

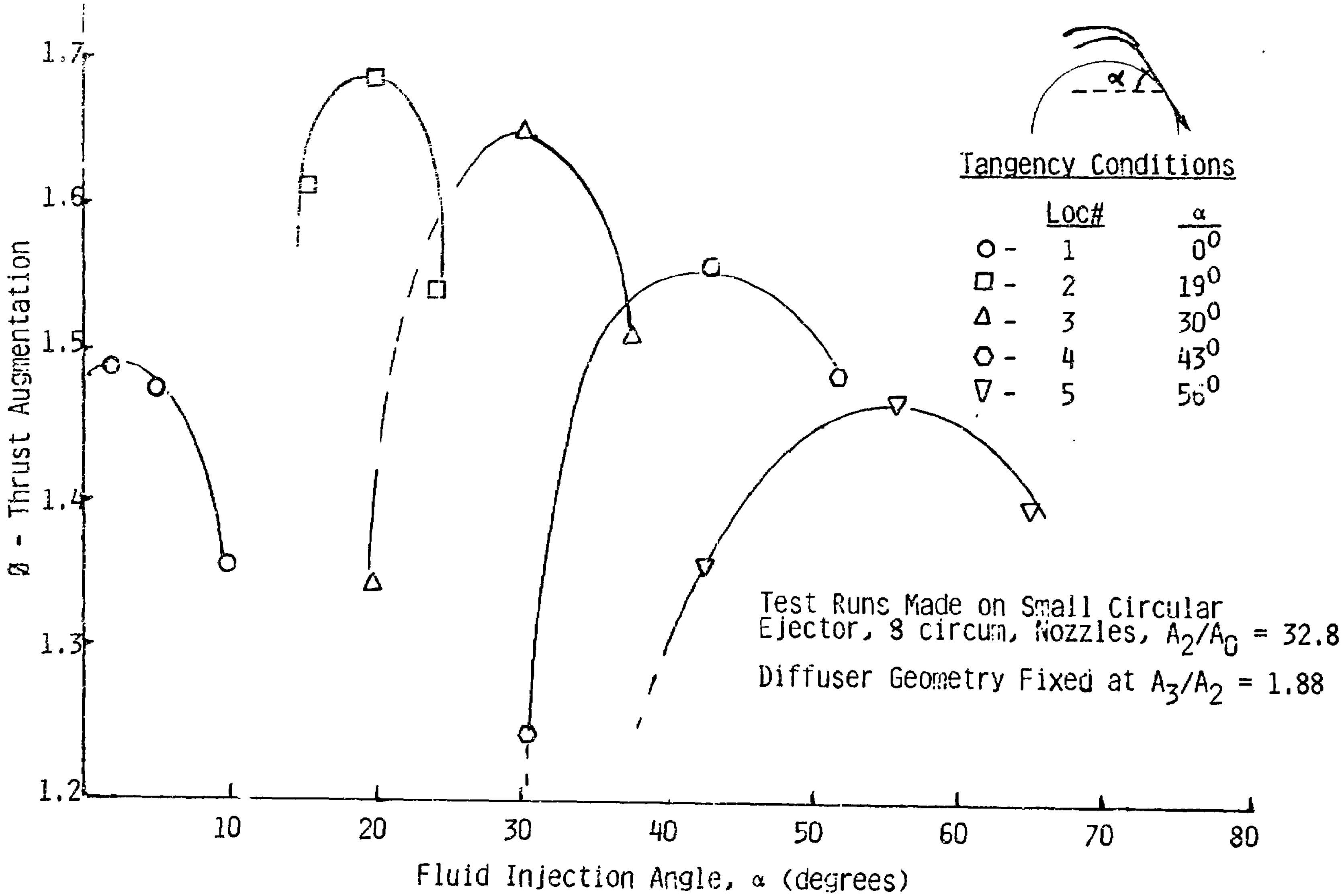


Figure 29. Effect of Primary Nozzle Position and Fluid Injection Angle on Thrust Augmentation

IV Conclusions

The following conclusions are based upon the results of this study:

1. Although mixing may be increased by installing thin plates in the ejector mixing chamber or in the diffuser, increased drag and turbulence decreases thrust augmentation.

2. Discrete fluid jets increase mixing as compared to a continuous slot configuration. Thrust augmentation is improved as long as the primary nozzles energize a sufficient portion of the inlet perimeter. Optimum thrust augmentation is achieved when approximately 40 to 60 percent of the inlet perimeter is "wetted" by the primary fluid jets.

3. Configurations which maintain a high energy flow of primary fluid near the diffuser walls permit the use of diffuser sections with high area ratios. For all configurations tested, thrust augmentation increased with diffuser area ratio, maximum ϕ occurring at values between 2.0 and 2.9.

4. Discrete primary nozzles which achieve Coanda flow at the throat gave superior performance over nozzle configurations that combined Coanda flow with the injection of primary fluid normal to the inlet.

5. For ejectors utilizing Coanda type flow at the throat, an approximate linear relationship exists between ϕ and A_3/A_0. This linear relationship may be helpful when designing ejectors for aircraft where diffuser geometry and nozzle dimensions are limited.

V Recommendations

Test results indicate significant increases in thrust augmentation can be obtained by positioning discrete nozzles about the ejector's inlet. The original Kedem designed ejector should be modified to allow various discrete nozzles to be symmetrically spaced around the entire inlet. The rectangular ejector is constructed to allow changes in the mixing chamber width and changes in the diffuser section length. Once an optimum configuration is determined, the discrete nozzles should be integrated into the inlet, as a single piece of hardware. This last modification would approximate the final engineering needed for integration into existing aircraft.

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Appendix A

Ejector Details

Rectangular Diffuser Geometry

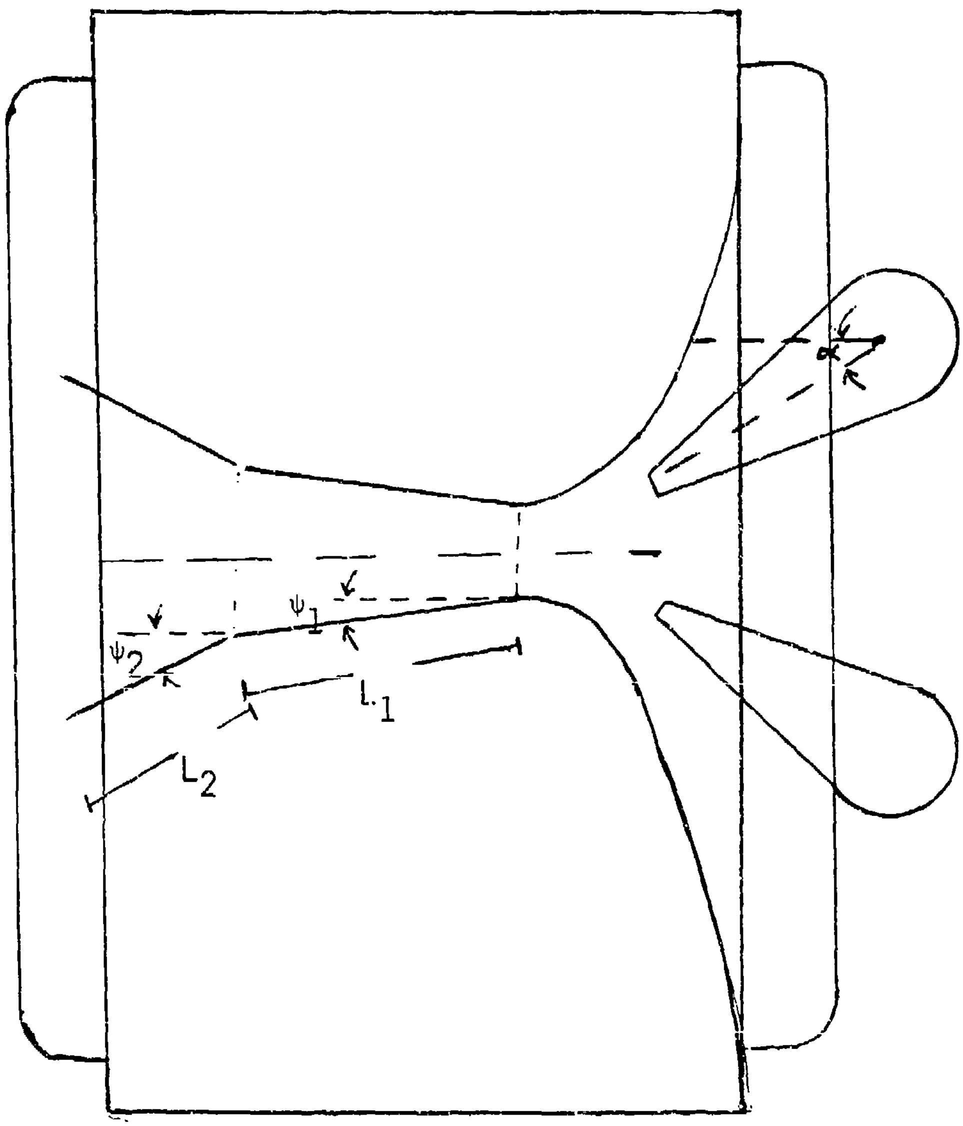
The rectangular ejector allowed for varying the diffuser half-angle while keeping the overall length constant (Fig A-1). The diffuser configurations tested and their designators are tabulated below:

TABLE A-1

Rectangular Ejector Diffuser Geometry

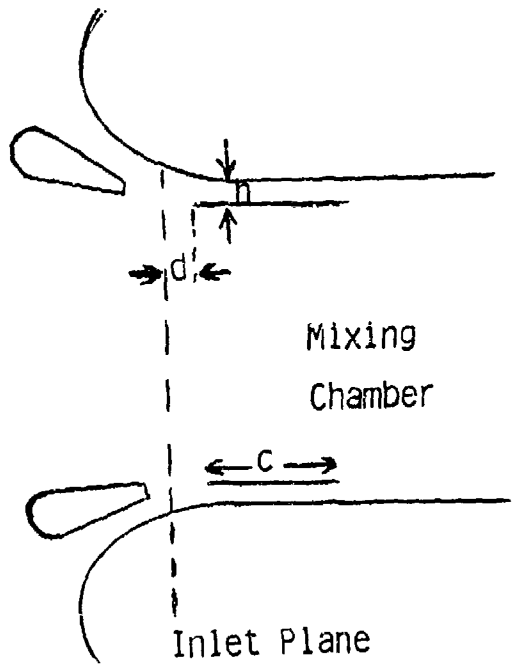
Diffuser Geometry ψ_1	Diffuser Geometry ψ_2	Designator
0°	3°	RD03
0°	6°	RD06
0°	9°	RD09
3°	0°	RD30
3°	2°	RD32
3°	3°	RD33
3°	4°	RD34
3°	6°	RD36
4°	4°	RD44

Side-View



L_1 - Mixing Chamber Length (3.1 in)
L_2 - Diffuser Length (5.5 in)
ψ_1 & ψ_2 - Diffuser Half Angles (variable)
α - Fluid Injection Angle (variable)

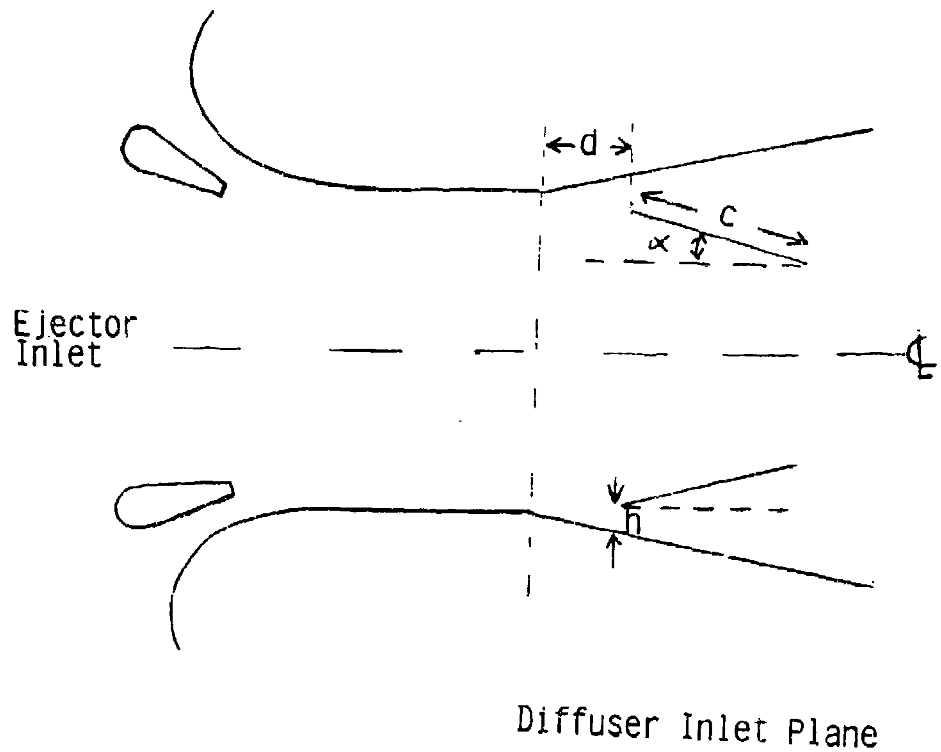
Figure A-1. Rectangular Ejector Nozzle Locations and Geometric Parameters



Configurations Tested

h = 0.5 in, 1.0 in
d = 0.0 in, 1.0 in
c = 1.0 in, 2.0 in, 3.0 in

Figure A-2. Mixing Chamber Plates Details



Configurations Tested

d = 0.0 in, 1.0 in
c = 1.0 in, 2.0 in, and 3.0 in
h = 0.5 in, 1.0 in
α = 0 to 8 degrees

Figure A-3. Diffuser Plates Details

4.4 in Diameter Circular Ejector

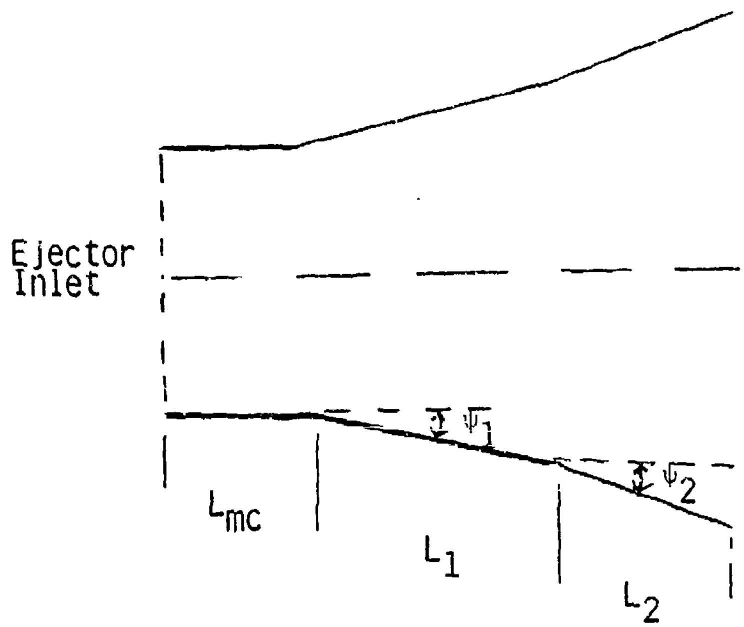
The diffuser sections were made of fiberglass or cardboard. The conic section length (L) and half-angle (ψ), where measured with respect to the ejector's center line (Fig A-4).

Diffuser configurations and their designators are presented in Table A-2.

TABLE A-2

4.4 in Ejector Diffuser Geometry

ψ_1	L_1	ψ_2	L_2	ψ_3	L_3	ψ_4	L_4	Designator
3 in mixing chamber only								SC00
3°	3.5 in							SC3
3°	3.5 in	7°	3.5 in					SC37A
3°	3.5 in	7°	3.5 in					SC37B
3°	3.5 in	8°	3.5 in					SC38A
3°	3.5 in	8°	4.5 in					SC38B
3°	3.5 in	7°	4.5 in	3°	3.5 in	7°	4.5 in	SC3737
3°	3.5 in	7°	4.5 in	3°	5.0 in	4°	6.0 in	SC3734
3°	3.5 in	7°	4.5 in	10°	7.0 in			SC3710
10°	9.0 in							SC10A
10°	12.0 in							SC10B



L_{mc} = Mixing Chamber Length (constant 3 in)

$L_{1,2}$ = Conic Diffuser Section Lengths (variable)

$\Psi_{1,2}$ = Diffuser Half-Angle (variable)

Figure A-4. Circular Ejector Details

6 in Diameter Ejector

The diffuser geometry for the large ejector was defined in the same way as the small ejector. Configurations and their designators are tabulated (Table A-3).

TABLE A-3

6 in Ejector Diffuser Geometry

ψ_1	L_1	ψ_2	L_2	Designator
3 in mixing chamber only				LC00
3°	5.0 in			LC3
3°	5.0 in	4°	6.0 in	LC34
3°	3.5 in	7°	4.5 in	LC37
3°	5.0 in	8°	6.0 in	LC38
10°	3.5 in			LC10A
10°	7.0 in			LC10B
10°	12.0 in			LC10C
10°	17.0 in			LC10D

Appendix B

Tabulated Results

TABLE B-1

Rectangular Ejector With Original Nozzles

$A_2/A_0 = 16$

Diffuser Configuration	A_3/A_2	$\emptyset$
RD06	1.5	1.34
RD30	1.4	1.30
RD33	1.67	1.36
RD35	1.8	1.37
RD36	1.93	1.40
RD39	2.2	1. $\pm$ stalls

TABLE B-2

Rectangular Ejector With 8 Discrete Jets

$A_2/A_0 = 22$

Diffuser Configuration	A_3/A_2	$\emptyset$
RD03	1.26	1.3
RD06	1.52	1.52
RD09	1.8	1. $\pm$ stalls
RD30	1.4	1.31
RD32	1.58	1.58
RD33	1.67	1.56
RD34	1.75	1.48 intermittent stall
RD36	1.93	stalls
RD44	1.9	stalls

TABLE B-3

4.4 in Ejector 8 Circumferential Nozzles

Spacing 1.2 in, $A_2/A_0 = 32.8$

Diffuser Configuration	A_3/A_2	$\emptyset$
SC00	1.0	1.26
SC37A	1.6	1.76
SC37B	1.78	1.80
SC38B	1.88	1.82
SC3837	2.7	1.86
SC3734	2.85	1.91
SC3710	3.8	1. $\pm$ stalls

TABLE B-4

4.4 in Ejector 12 Circumferential Nozzles

Spacing .47 in, $A_2/A_0 = 21.8$

Diffuser Configuration	A_3/A_2	$\emptyset$
SC38B	1.88	1.70
SC3734	2.85	1.82
SC10B	3.8	1. $\pm$ stalls

TABLE B-5

4.4 in Ejector 16 Circumferential Nozzles

Spacing .1 in, $A_2/A_0 = 16.4$

Diffuser Configuration	A_3/A_2	$\emptyset$
SC3	1.17	1.27
SC37B	1.78	1.56
SC3837	2.7	1.63
SC10A	2.9	1.64
SC10B	3.8	1. $\pm$ stalls

TABLE B-6

4.4 in Ejector 8 Circum/8 Spoke Nozzles
Spacing .1 to .57 in, A_2/A_0 = 18.8

Diffuser Configuration	A_3/A_2	Ø
SC00	1.0	1.1
SC3	1.17	1.28
SC37B	1.78	1.53
SC38B	1.88	1.54
SC3837	2.7	1.62
SC10A	2.9	1.34 intermittent stall

TABLE B-7

4.4 in Ejector Annular Nozzle
A_2/A_0 = 12.67

Diffuser Configuration	A_3/A_2	Ø
SC00	1.0	1.2
SC3	1.17	1.29
SC38A	1.7	1.48
SC38B	1.88	1.60
SC10A	2.9	1.69
SC10B	3.8	1.5 intermittent stall

TABLE B-8

6 in Ejector 8 Circum Nozzles
Spacing 1.72 in, A_2/A_0 = 61

Diffuser Configurartion	A_3/A_2	Ø
LC00	1.0	1.38
LC3	1.18	1.65
LC34	1.5	1.81
LC37	1.55	1.80
LC38	1.88	1.70
LC10B	2.0	1. ± stalls

TABLE B-9

6 in Ejector 12 Circum Nozzles

Spacing .88 in, A_2/A_0 = 40.6

Diffuser Configuration	A_3/A_2	Ø
LC00	1.0	1.28
LC3	1.18	1.46
LC10A	1.45	1.51
LC34	1.5	1.57
LC38	1.88	1.77
LC10B	2.0	1.82
LC10C	2.9	1.88
LC10D	3.9	1.3 ± stalls

TABLE B-10

6 in Ejector 16 Circum Nozzles

Spacing .41 in, A_2/A_0 = 30.5

Diffuser Configuration	A_3/A_2	Ø
LC00	1.0	1.28
LC3	1.18	1.48
LC34	1.5	1.52
LC37	1.55	1.58
LC38	1.88	1.72
LC10B	2.0	1.75
LC10C	2.9	2.0
LC10D	3.9	1.3 ± stalls

TABLE B-11

6 in Ejector 8 Circum/8 Spoke

Spacing .41 to .83, A_2/A_0=35

Diffuser Configuration	A_3/A_2	Ø
LC00	1.0	1.3
LC34	1.50	1.67
LC37	1.55	1.68
LC10B	2.0	1.6
LC10C	2.9	1.3 ± stalls

Appendix C

Data Reduction and Error Analysis

Primary Nozzle Pressure Readings

Total pressure readings were taken using small diameter pressure taps located in the primary nozzle plena. Due to the low velocity flows (20 fps in the rectangular ejector, 85 fps in the circular ejector nozzles), static pressure readings were assumed equivalent to stagnation pressure. Using Bernoulli's equation a rough estimate of the error in p_t readings can be calculated:

$$\frac{\Delta p}{P_t} \sim \frac{V^2}{2\ R\ T} \sim \frac{85^2}{2(32.2)(53.4)(540)} \sim .0038$$

This error was on the same order of accuracy of the manometer board readings, i.e. $p_t = p_a + 4(\text{in Hg}) \pm 0.05$ (in Hg). The pressure readings were accurate within $\pm$ 1 percent.

Primary Nozzle Dimensions

The slot nozzles used during this investigation were measured using a Gaertner Scientific Corporation Microscope. Measurements were accurate within 0.00032 in. The slot nozzle xit dimensions were not uniform within this 0.0002 in accuracy; therefore, average lengths and widths were calculated for each nozzle. Among a given set of nozzles, exit areas varied approximately $\pm$2 percent. An average exit area was calculated for each type of nozzle tested and this average was subsequently used in all calculations, e.g. $F_i = 7\ A_{nozzle}\ P_a((p_t/p_a)^{.286} - 1)$.

Thrust Measurements

Thrust measurements were taken using a strain gage load cell, mounted to the floor and connected to the test stand via a system of cables and adjustable pulleys. A simple weight platform, also connected to the test stand, was used to calibrate the strain gage load cell.

During calibration, tests, the system exhibited a slight hysteresis. Additionally, any vibrations during the tests caused a scatter of 8 percent. Scatter and hysteresis were attributed to the friction in the pulleys. By inducing vibrations during the calibration runs, the scatter in data points was reduced to ± 1 percent (Fig C-1). Vibrations were induced by tapping the steel cables, connecting the platform to the test stand, with a slender steel rod until the strain indicator readings remained constant. To insure friction and/or unavoidable vibrations did not adversely affect ejector thrust measurements, the pulley cables were vibrated, as described above, for all test runs.

Thrust Augmentation Ratio Calculations

The thrust augmentation ratio, Ø, is defined as F_m/F_i, where F_m is the measured thrust and F_i is the isentropic thrust. F_i is defined as:

$$F_i = 7\ A\ (p_a)\ ((p_t/p_a)^{.286} - 1)$$

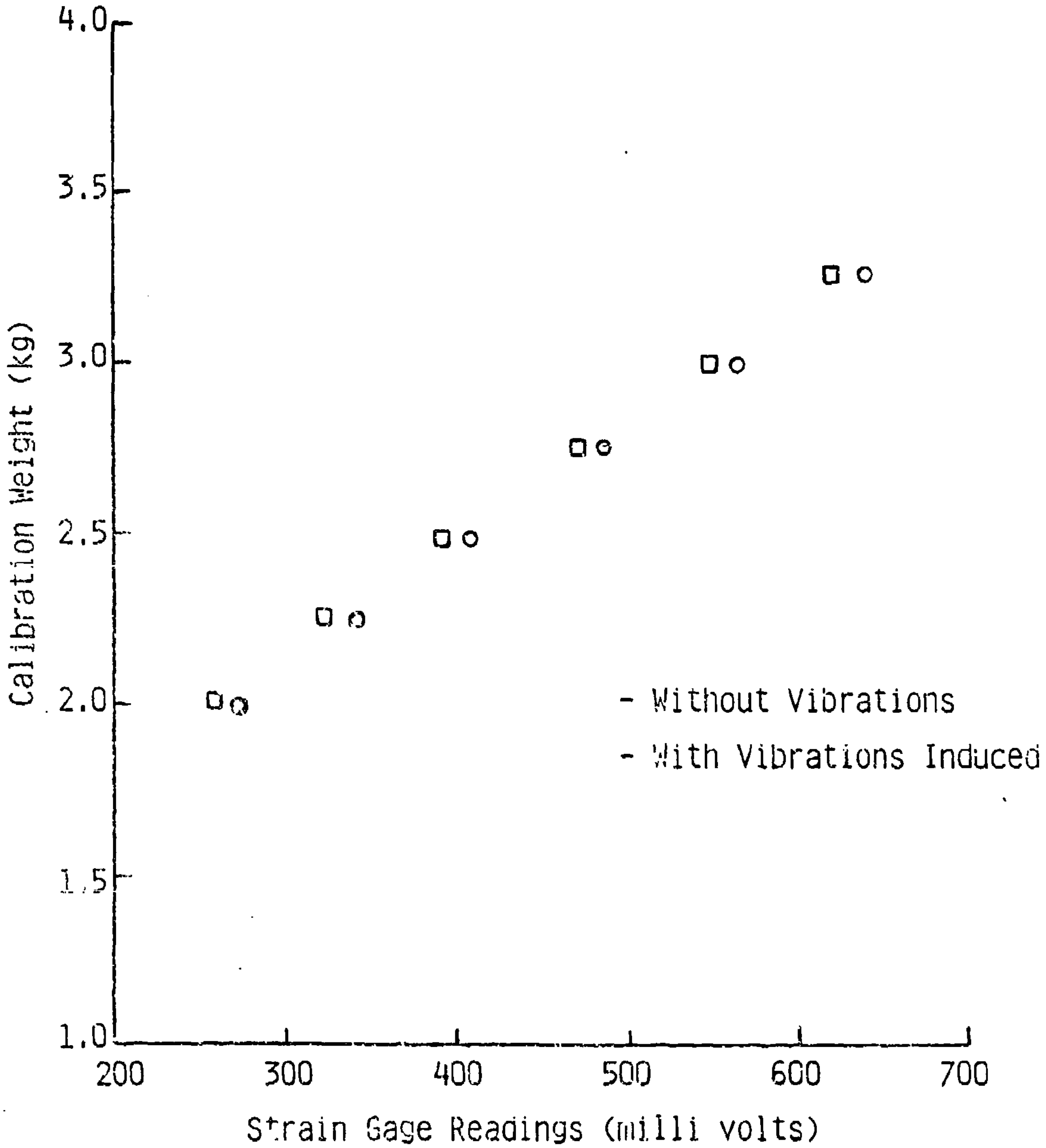


Figure C-1. Effect of Vibrations on Test Stand Force Measurements

By introducing errors into a sample calculation of Ø, a rough estimate concerning the accuracy of the calculated thrust augmentation ratios was determined. Ø was determined to be accurate within ± 4 percent. With all values tending to be optimistic by 2 percent due to the earlier discussed assumptions of p_t being assumed equivalent to p_a in the nozzle plena. Ø measurements throughout this investigation were repeated within a bandwidth of ± 2 percent; therefore all trends indicated in the graphs presented can be assumed accurate within this ± 2 percent band.

Primary Nozzle Thrust Efficiency

Primary nozzles were installed on a shroudless wood ring, discussed in Section II, and thrust measurements were taken for primary to ambient pressure ratios of 1 to 1.14. Thrust efficiency is defined as F_m/F_i, where F_m is the measured thrust and F_i is the isentropic thrust. All primary nozzles used during this investigation had approximately the same efficiencies regardless of their shape or slot dimensions. Thrust efficiencies ranged from .94 to .98 with a scatter of ± 2 percent.

VITA

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A short rectangular ejector and two circular ejectors were tested to determine the effects of primary nozzle configuration and geometry on thrust augmentation. The primary nozzle configurations consisted primarily of slot nozzles which injected fluid parallel to the diffuser walls and achieved Coanda type flow at the throat.

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Results of the rectangular ejector tests indicate that thin plates installed in the mixing chamber or the diffuser, increase mixing but decrease thrust augmentation. A continuous slot nozzle, modified to create four discrete jets at the inlet, improved mixing and thrust augmentation compared to the original design. Thrust augmentation ratio increased from 1.4 to 1.58.

The circular ejector primary nozzles consisted of a continuous slot "torus" nozzle and individual slot nozzles which could be symmetrically placed around the inlet periphery. A nozzle configuration using 16 slot nozzles on the periphery of the inlet face gave the best performance. A thrust augmentation ratio of 2.0 was acheived.